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HEMP SIMULATION TESTS

FINAL TEST REPORT, Sanifized Version

W. A. Bereuter S. M. Dunivin

Revised 10 September 1992

Prepared for:

Director

Defense Nuclear Agency 6801 Telegraph Road

Alexandria, VA 22310-3398 Contract No. DNA001-91-C-0093

CDRL item No. 16

Prepared by:

MISSION RESEARCH CORPORATION

4935 North 30th Street

Colorado Springs, CO 80919

This work sponsored by the Defense Nuclear Agency
RDT&E RMSS CODE: B 4662 D RV RD 00128 3400 A AF

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### PREFACE

This work was sponsored by the Defense Nuclear Agency under the Advanced FGBC4I EMP Testing (AFEMPT) program. The DNA project officer for this effort is MAJ Michael R. Rooney.

## CONVERSION TABLE

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#### SECTION 1

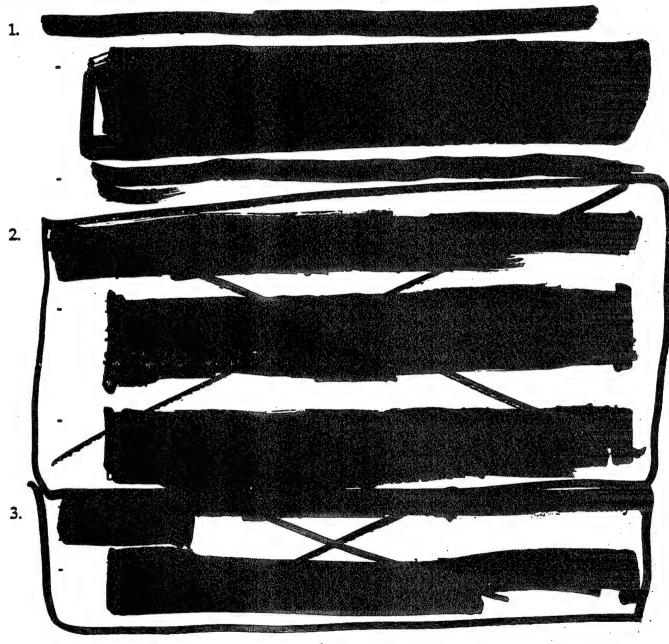
## INTRODUCTION

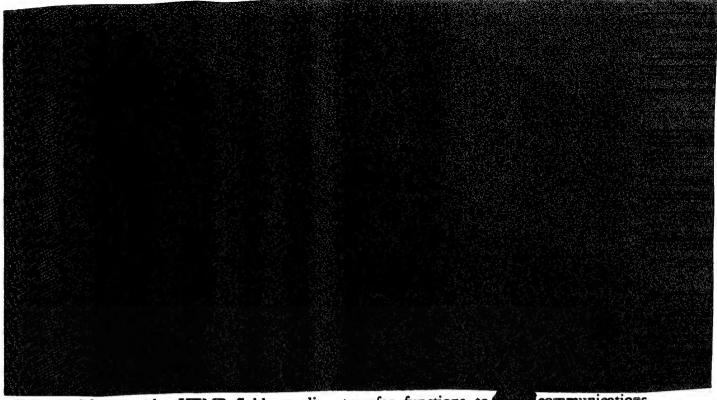
This report documents the results from the tests conducted

8 May to 17

June 1992.

The overall purpose of the test was to acquire test data to support the further development of MIL-STD-188-125 (Reference 1), and to demonstrate the test requirements in this standard in practice. The tests addressed the following objectives:





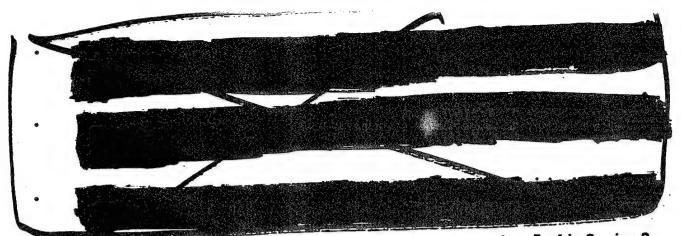
- 5. Measure the HEMP field coupling transfer functions to communications antennas.
  - To define waveforms for injecting antenna lines, and thus verify the hardness of radio equipment against HEMP, measurements at typical antennas are necessary to ensure that the waveforms properly represent the induced threat transients.
  - Useful measurements at all antennas were acquired for this purpose.

DOD-STD-2169A specifies the HEMP field environments in terms of three time regimes: The early time (E1) field pulse, the intermediate time (E2) field pulse, and the late time (E3) field pulse.

All three environments induce current pulses on exposed electrical lines. MIL-STD-188-125 defines generic current pulses for each environment: The E1 field environment produces the Short Pulse, the E2 environment produces the Intermediate Pulse, and E3 produces the Long Pulse.

Unfortunately, the terminology of DOD-STD-2169A is now also widely used when referring to the coupled currents. For example, the Long Pulse is also known as "E3"; the corresponding pulser is called the "E3 pulser." This short-hand presumably does no harm as long as environments (in Volts/meter) and coupled currents (in Amps) are not confused.

The test addressed all three HEMP time regimes:



The tests and measurements acquired for objectives 1, 2, and 3 are described in Section 2. The Intermediate Pulse test data (objective 4) are contained in Section 3.

Section 4 documents the antenna coupling measurements (objective 5). The conclusions and recommendations are summarized in Section 5. For detailed descriptions of the test activities see Reference 2.

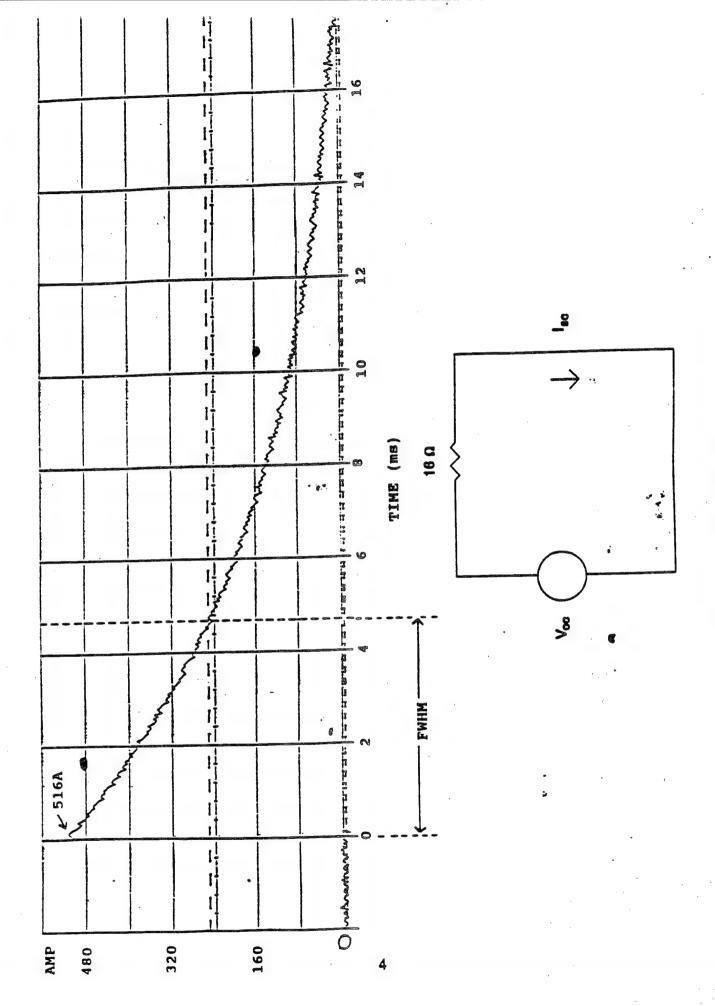
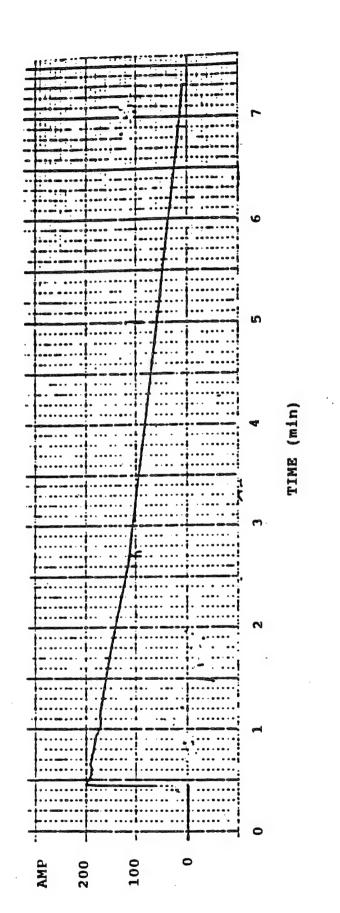


Figure 1-1. E2 pulser short circuit current.



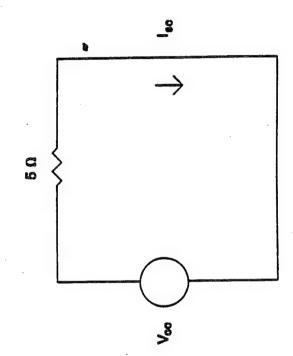
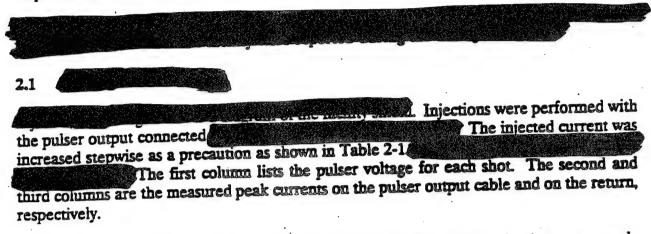


Figure 1-2. E3 pulser short circuit current.

#### SECTION 2

# LONG PULSE CURRENT (E3) INJECTIONS

The current waveform induced by MHD-EMP is specified in MIL-STD-188-125 as a double exponential waveform (200 A peak, less than 0.5 seconds rise time, and at least 100 seconds full-width-at-half-max). The waveform provided by the E3 pulser (Reference 3) meets these requirements.



Since the return current is equal to the pulser output current, all coulombs are properly accounted for; i.e., Kirchhoff's circuit equations are satisfied. The last column is the estimated path resistance ( $R_{path}$ ). It is in series with the pulser source impedance (5 ohms by design).  $R_{path}$  can be estimated from the peak pulser voltage  $V_p$  and the measured peak input or return current  $I_{med}$  as follows:

$$R_{PATH} = \frac{V_P}{I_{--}} - 5 \qquad (\Omega) \tag{2-1}$$

The calculated values in the last column of Table 2-1 indicate that the path resistance is less than 1 ohm

The waveforms were recorded transients were generally sampled every 1 ms. Thus, for a full E3 measurement, there are 360000 samples (9 Mbytes). Consequently, the full time history of the measurements cannot be plotted in a useful manner; instead, narrow time windows were selected in all following displays.

2-3 is the same pulse, but with the time scale expanded. The ripples on the E3 pulse

(evident on the blowup of the early time portion) 7

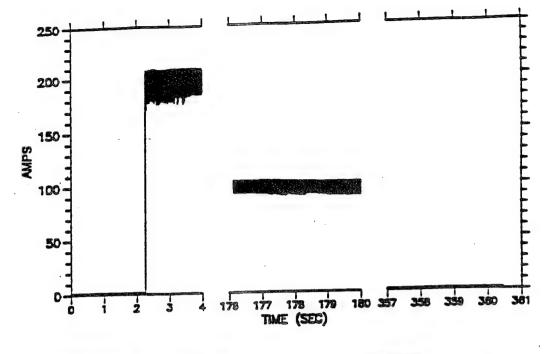


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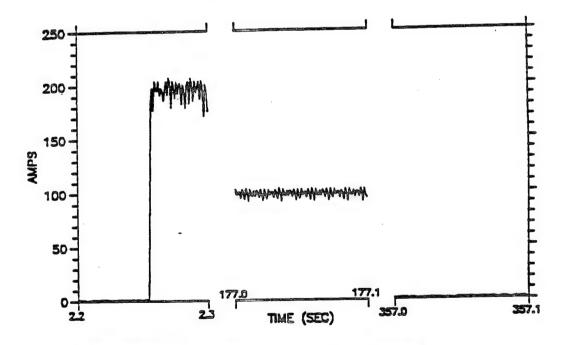


Figure 2-3. current injected at pulser voltage; expanded time scales (file 3C000ABC).

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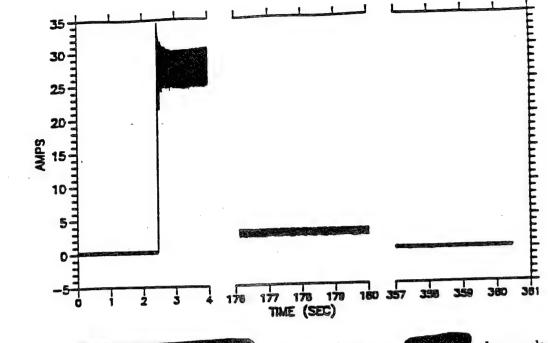


Figure 2-10. G17900AC).

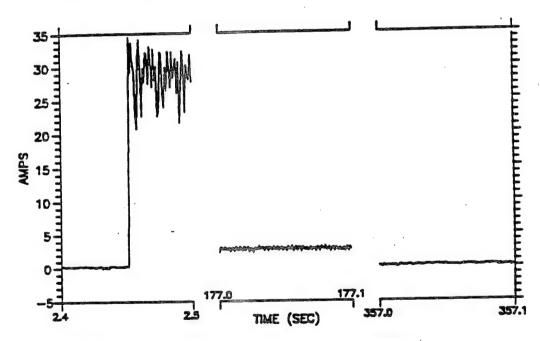


Figure 2-11. current injected at pulser voltage, expanded time scale (file G17900AC).

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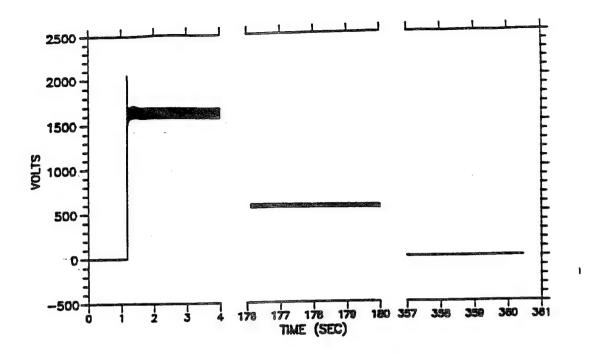


Figure 2-13. E3 common model ection, (file 3C0024AV).

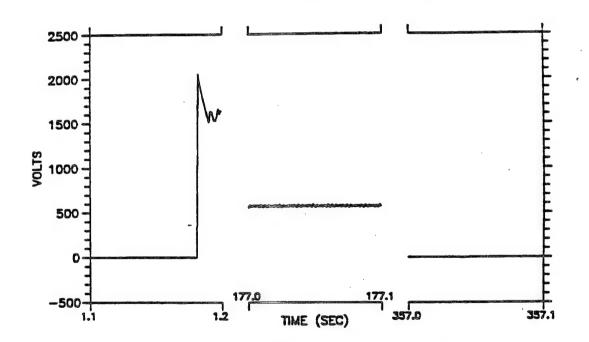
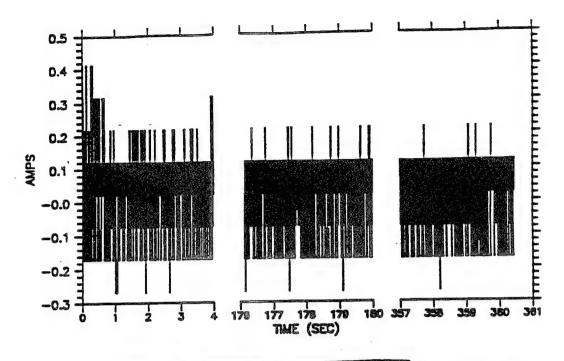


Figure 2-14. E3 common mode injection expanded time scale (file 3C0024AV).





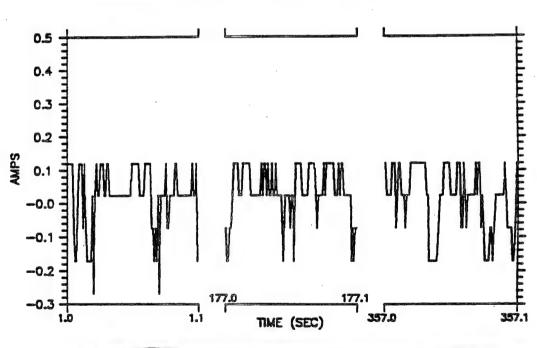


Figure 2-16. (file 3C0024AC).

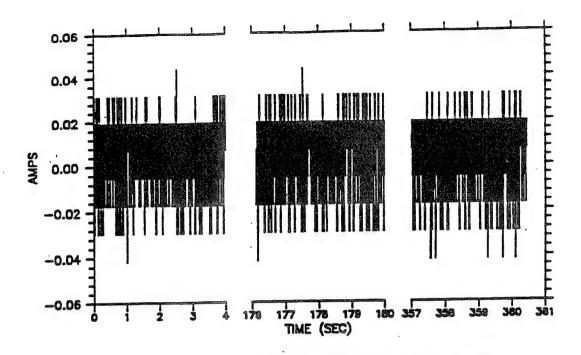


Figure 2-17. E3 common mode injection file 3C0025AC).

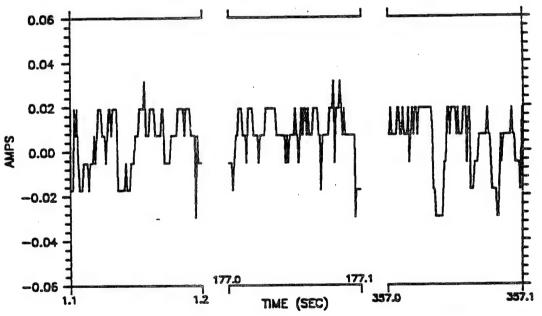


Figure 2-18. E3 common mode injection, expanded time scale (file 3C0025AC).

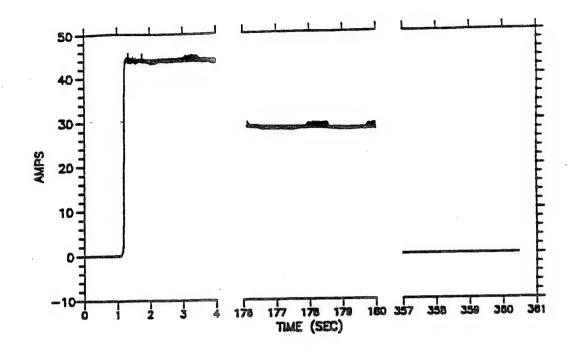


Figure 2-20. E3 wire-to-ground injection, input current (file 3A0021AC).

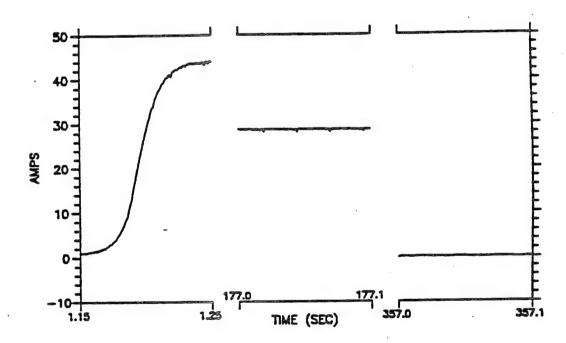


Figure 2-21. E3 wire-to-ground injection, input current expanded time scale (file 3A0021AC).

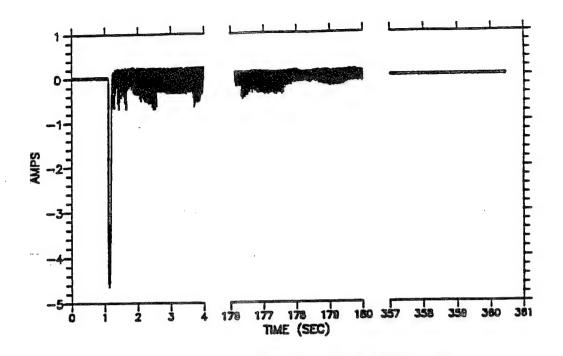


Figure 2-22. E3 wire-to-ground injection (file 3A0025BC).

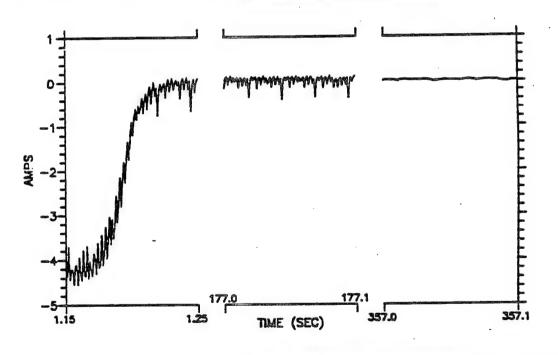


Figure 2-23. E3 wire-to-ground injection, expanded time scale (file 3A0025BC).

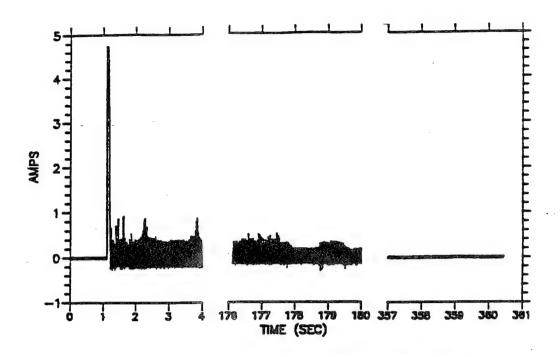


Figure 2-24. E3 wire-to-ground injection, file 3A0026BC).

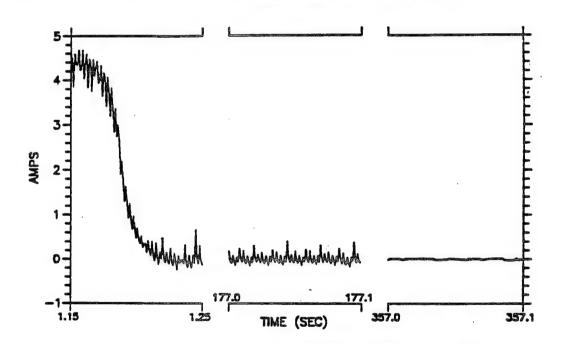


Figure 2-25. E3 wire-to-ground injection, expanded time scale (file 3A0026BC).

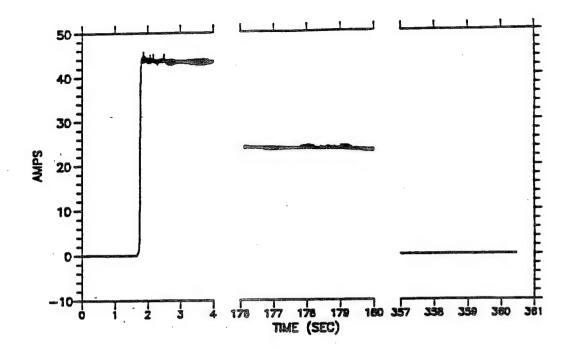


Figure 2-26. E3 wire-to-ground injection, input current (file 3A0021CC).

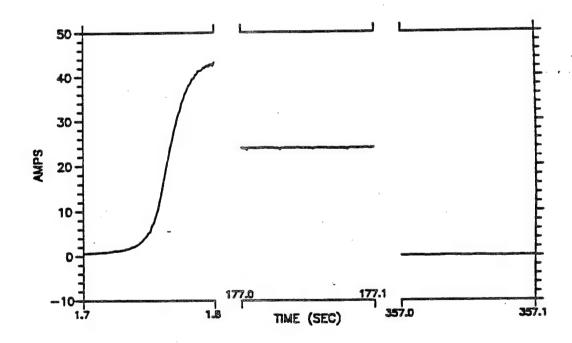


Figure 2-27. E3 wire-to-ground injection, input current expanded time scale (file 3A0021CC).

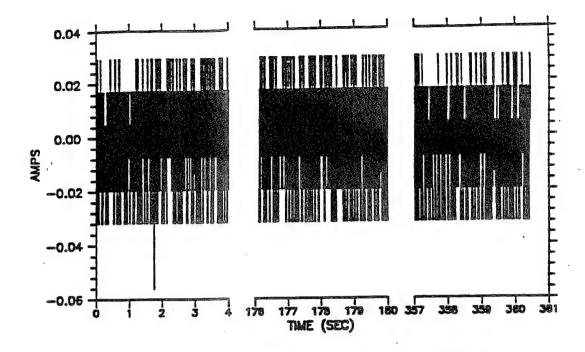


Figure 2-28. E3 wire-to-ground injection (file 3A0027BC).

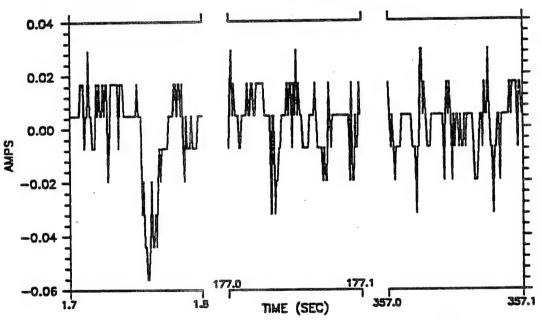


Figure 2-29. E3 wire-to-ground injection, expanded time scale (file 3A0027BC).

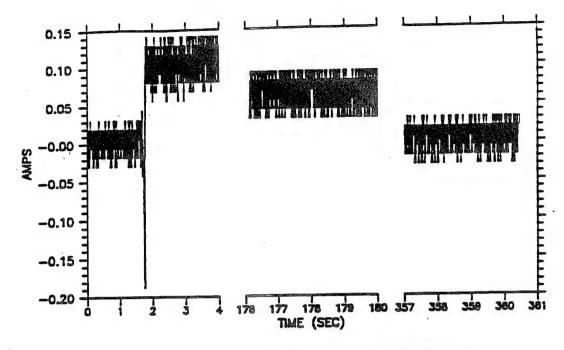


Figure 2-30. E3 wire-to-ground injection,

file 3A0028BC).

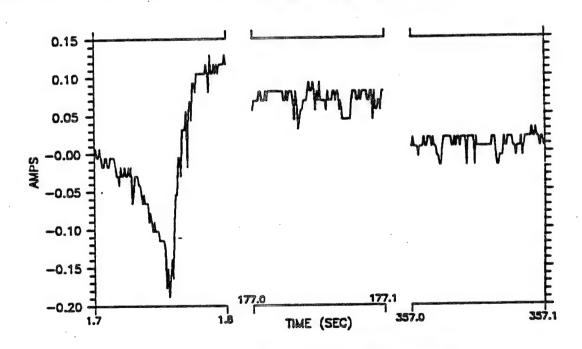
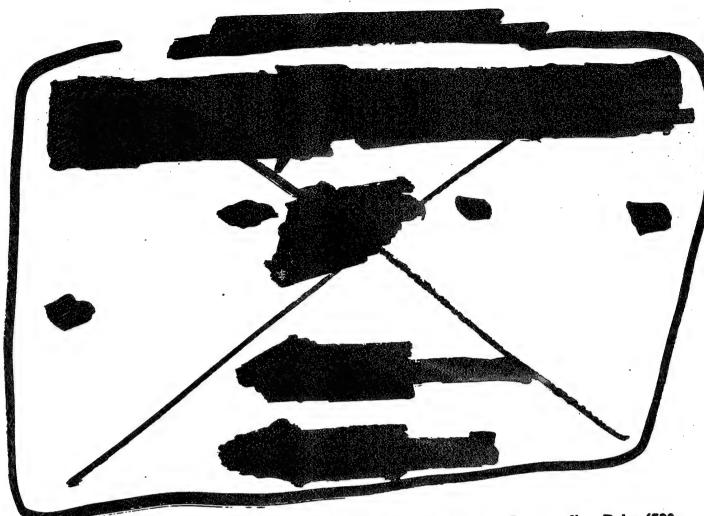


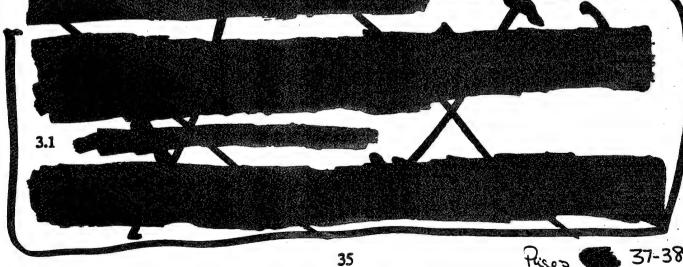
Figure 2-31. E3 wire-to-ground injection (file 3A0028BC).

expanded time scale

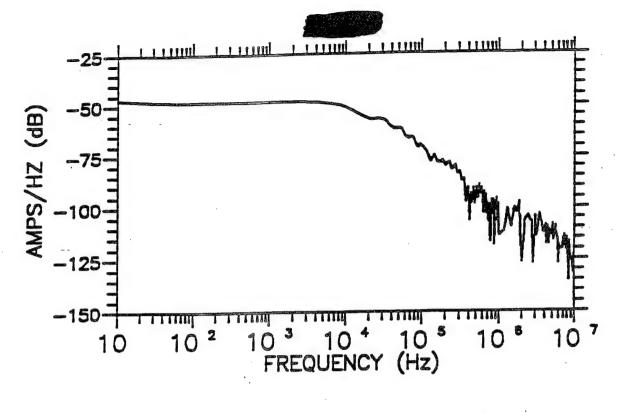
Pages 27-34 removed in their entirety,



The E2 pulser meets the requirements of MIL-STD-188-125 for the Intermediate Pulse (500 A peak, less than 1 us rise time, and more than 0.5 ms full-width-at-haif-max).



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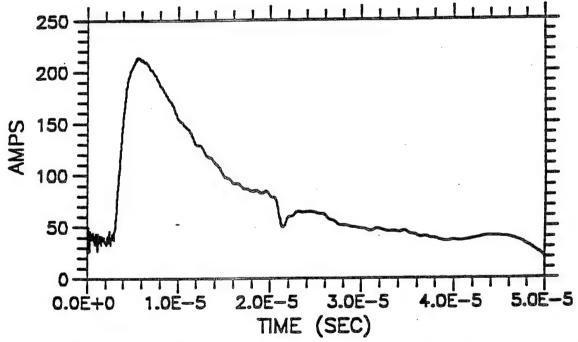
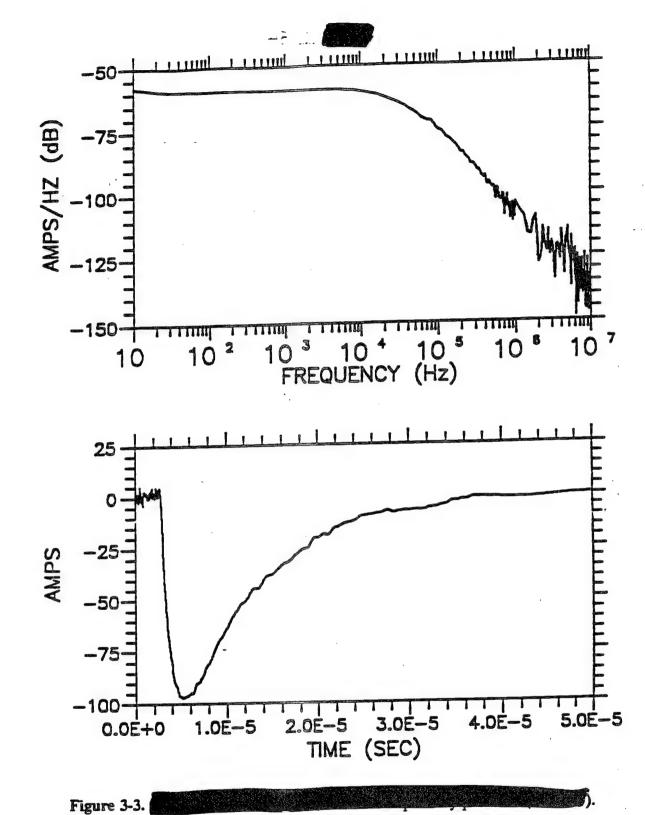
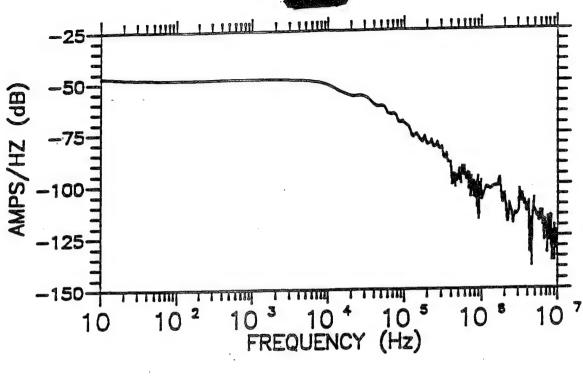


Figure 3-2.





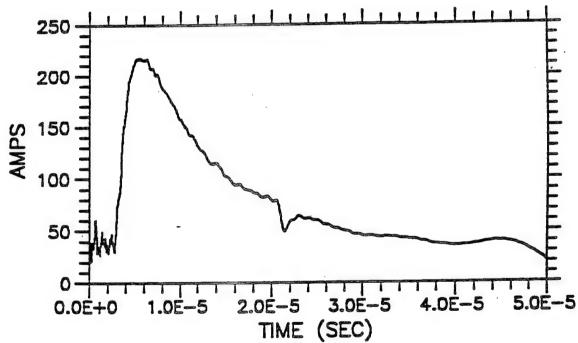
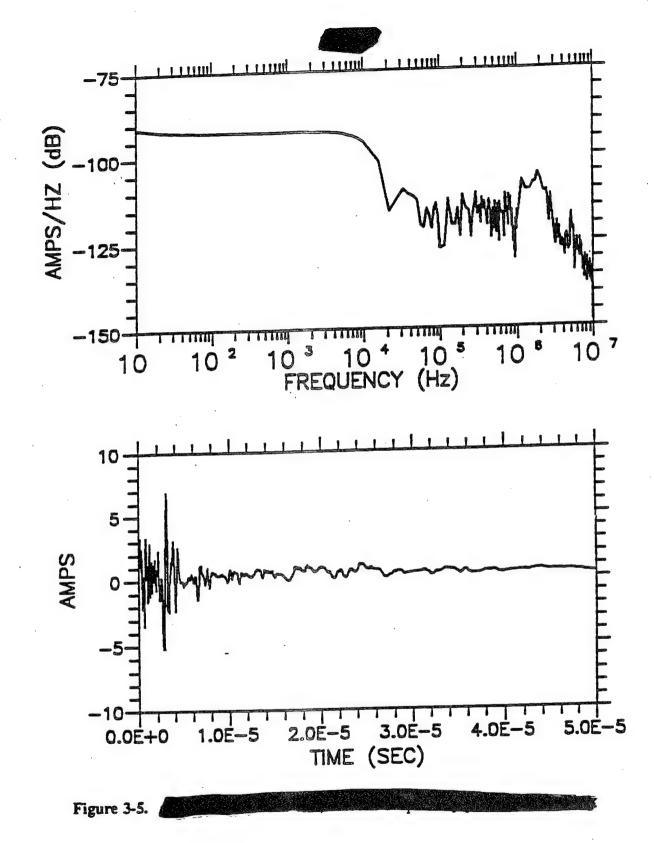


Figure 3-4.



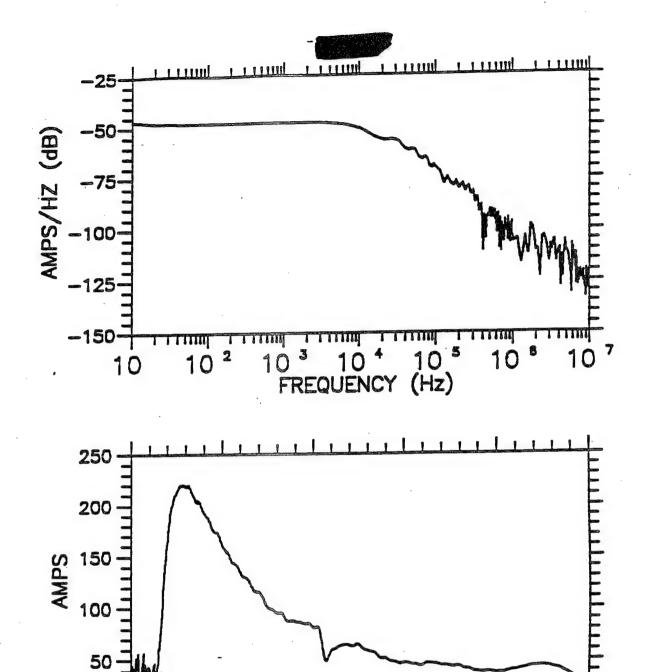


Figure 3-6.

1.0E-5

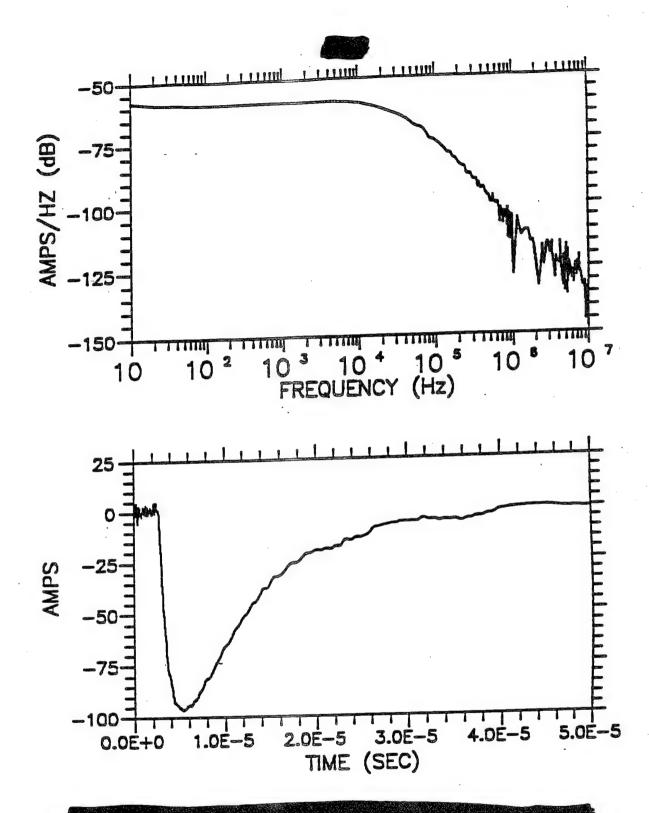
0.0E+0

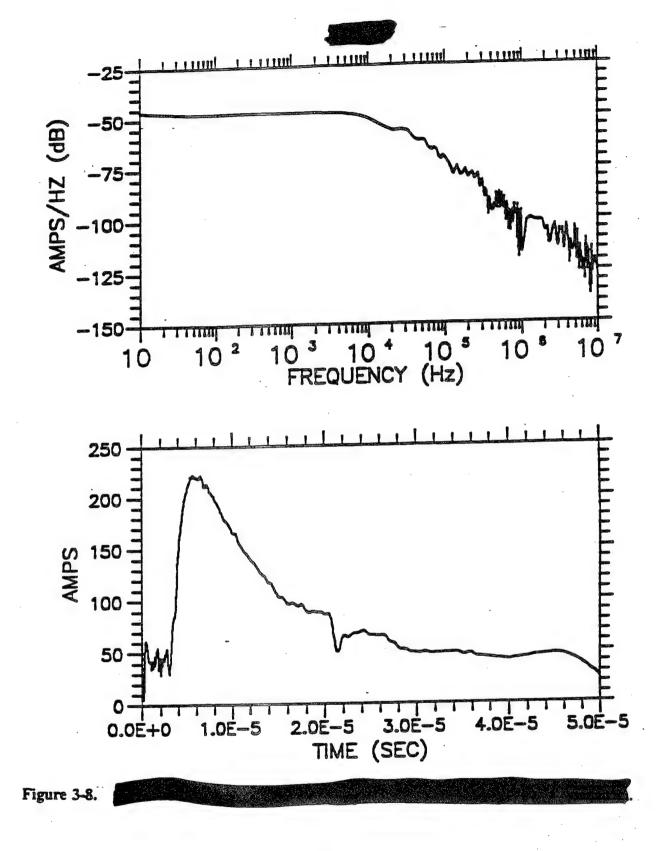
2.0E-5

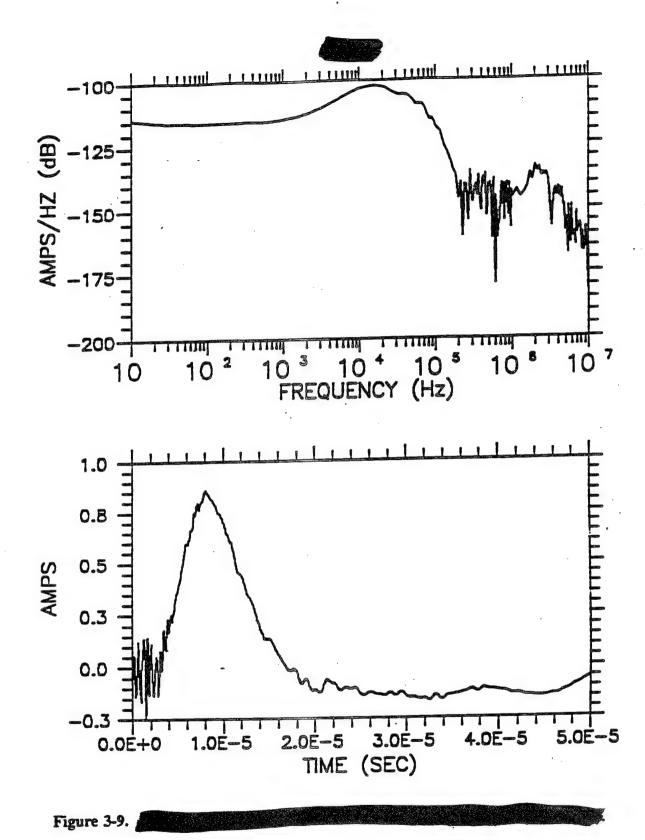
TIME (SEC)

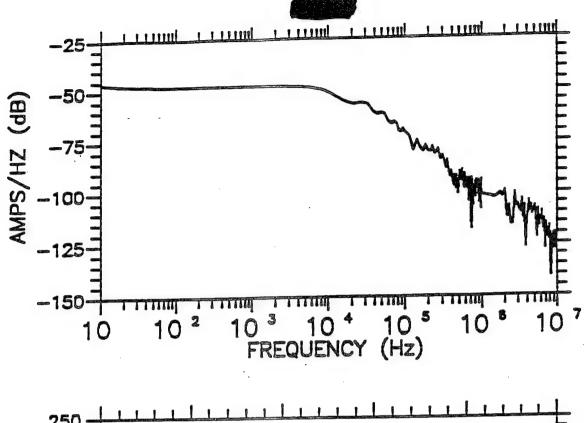
3.0E-5

4.0E-5









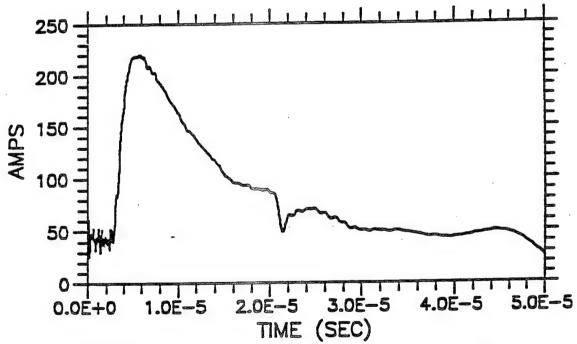


Figure 3-10.

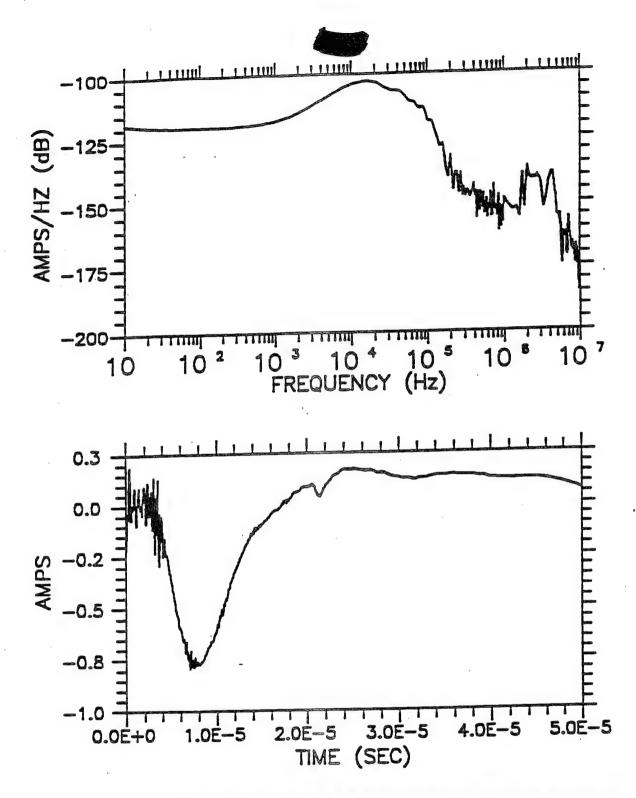
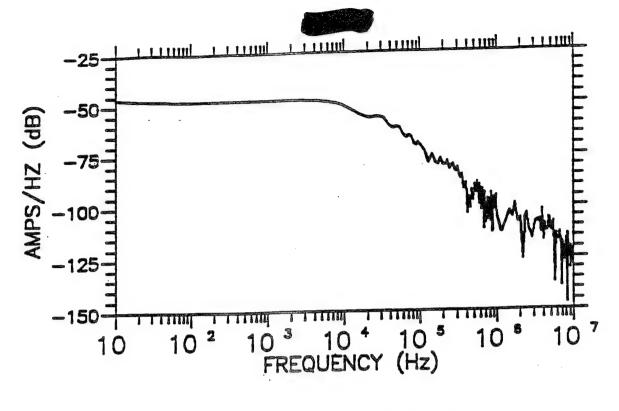


Figure 3-11.



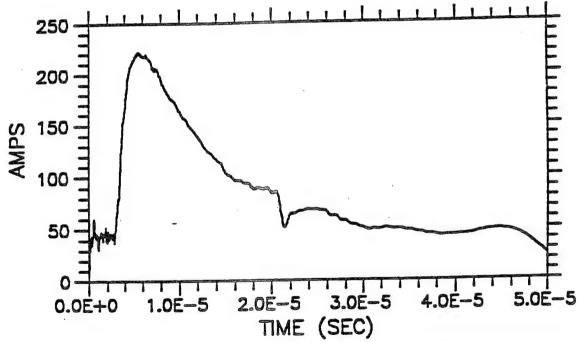
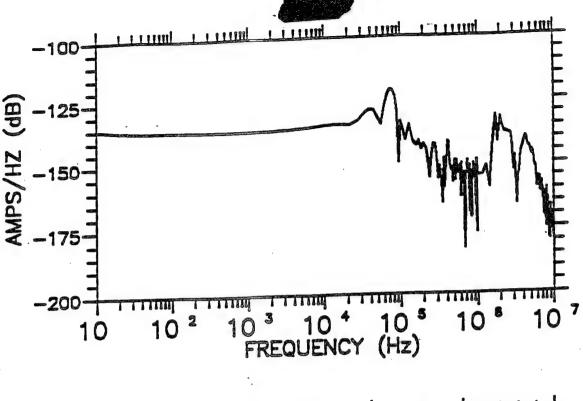


Figure 3-12.



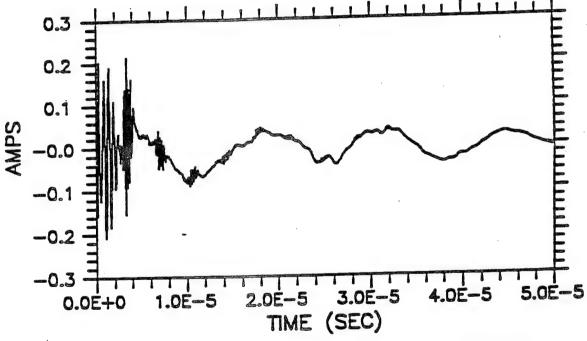
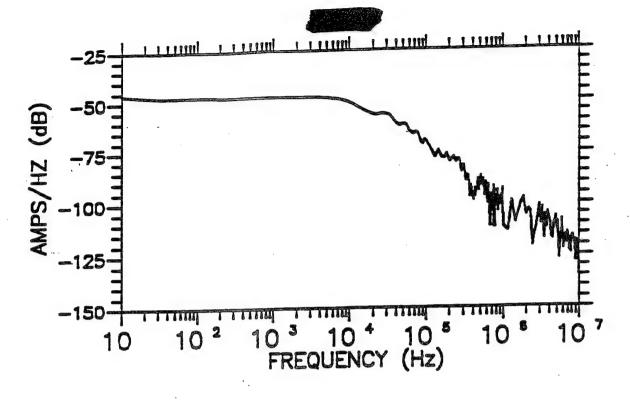


Figure 3-13. **Same** 



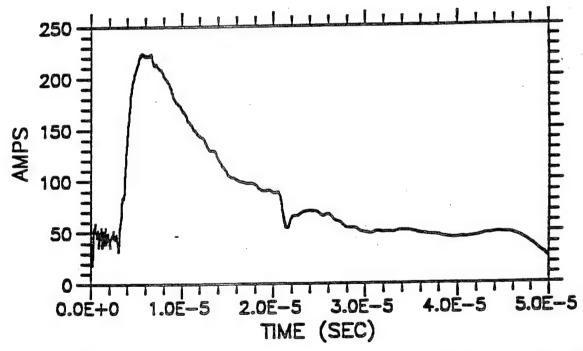


Figure 3-14.

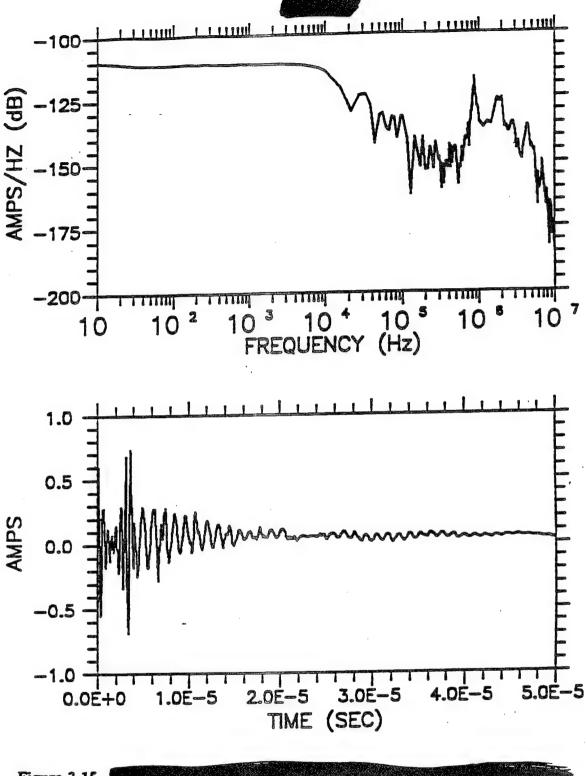


Figure 3-15.

Pages 53-55 nemoved in their entirety,

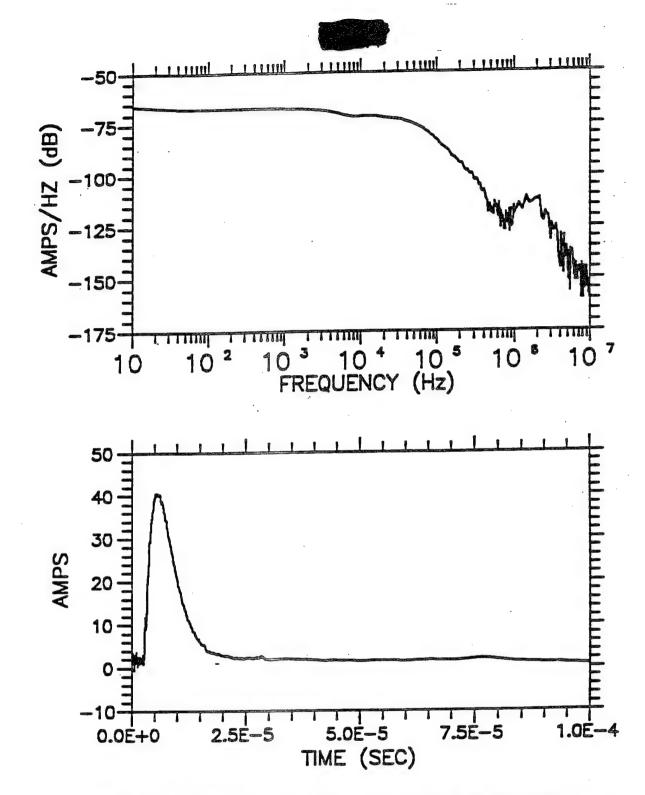


Figure 3-17

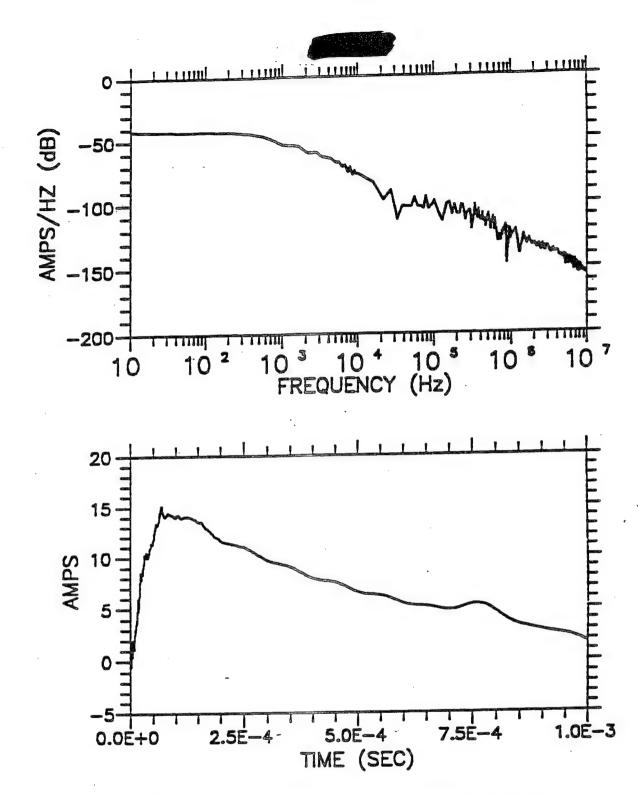
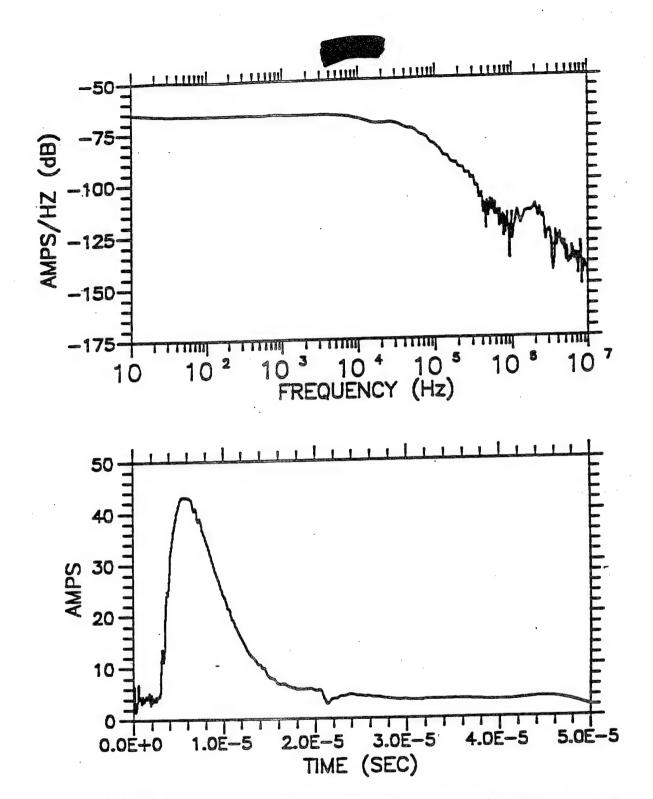
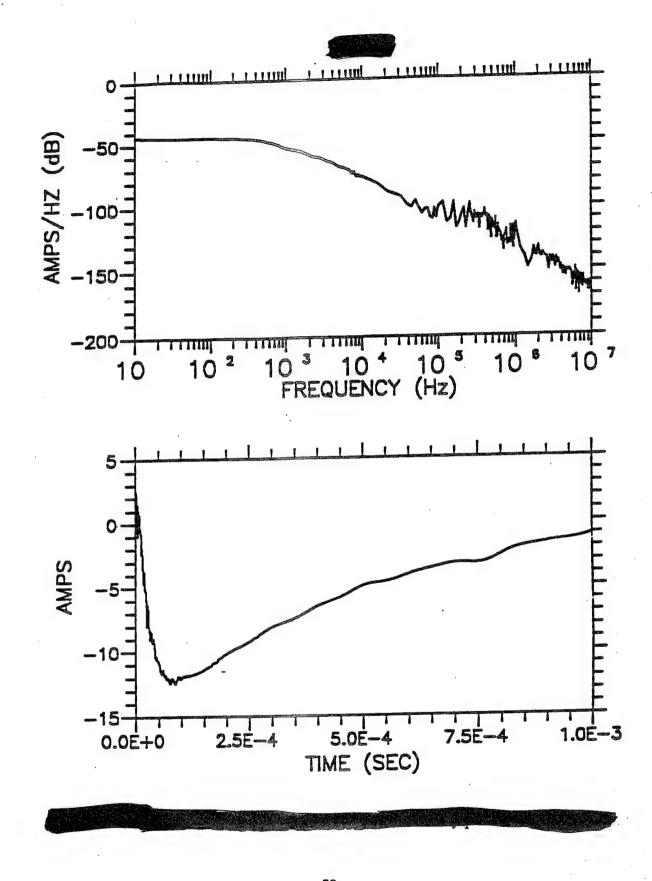
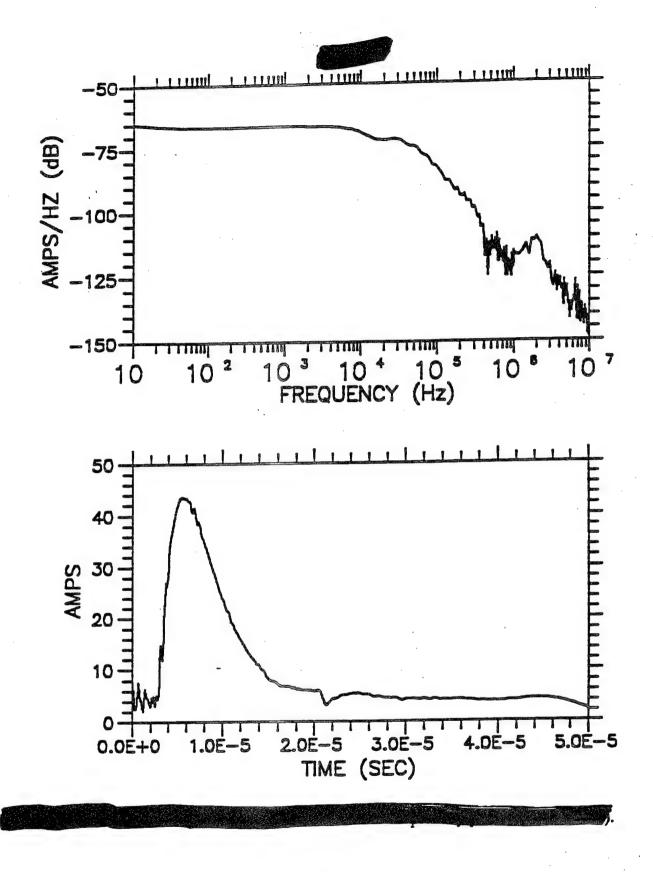
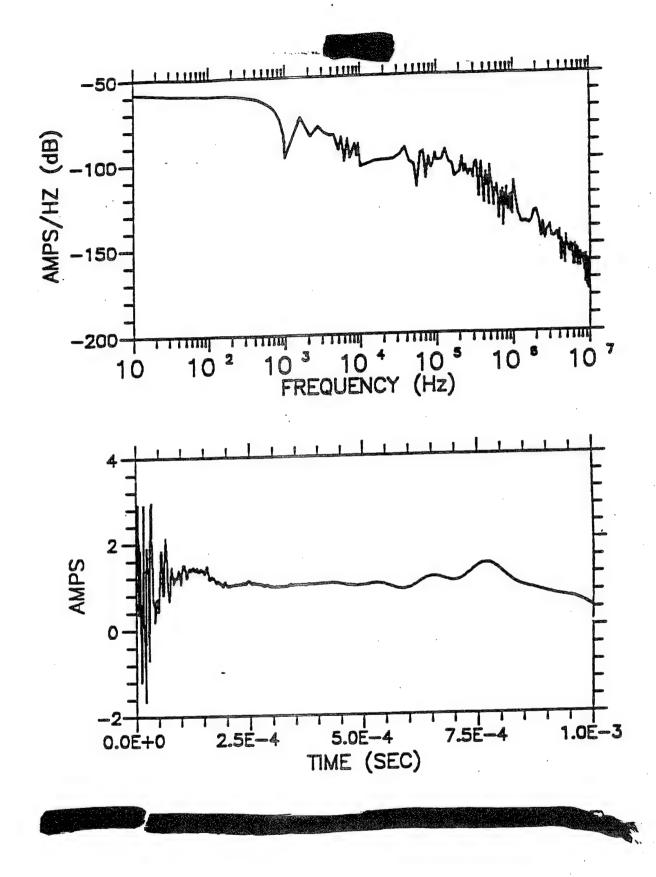


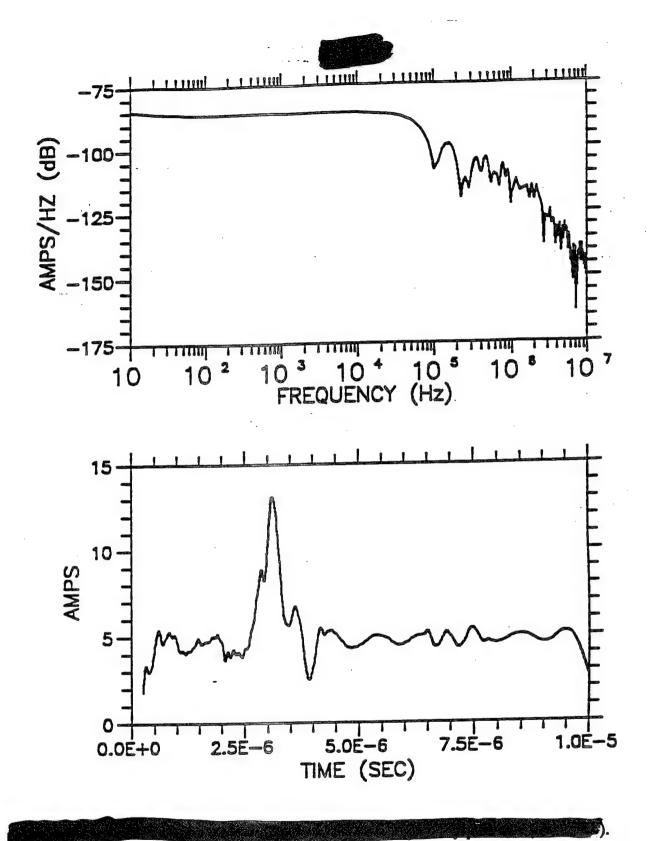
Figure 3-18.

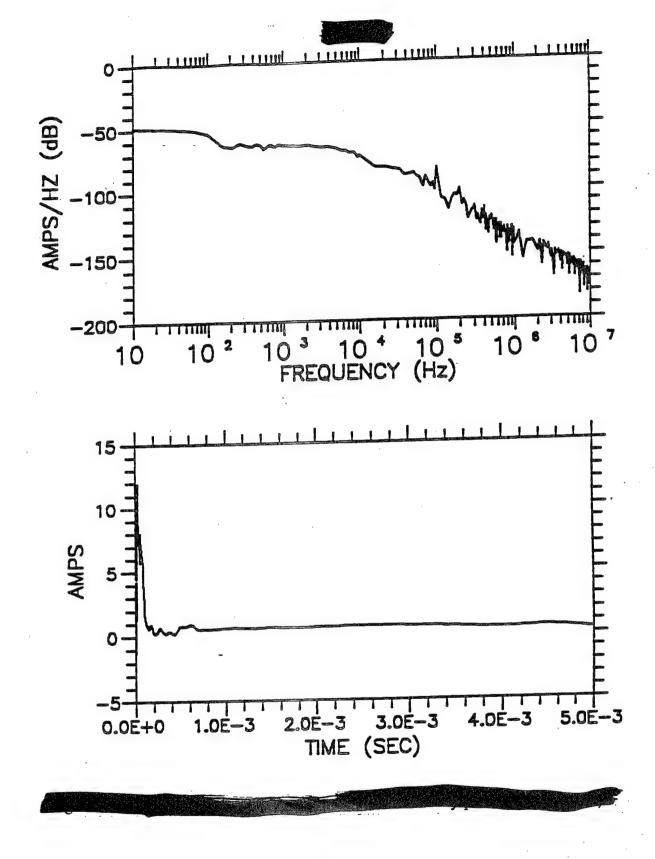


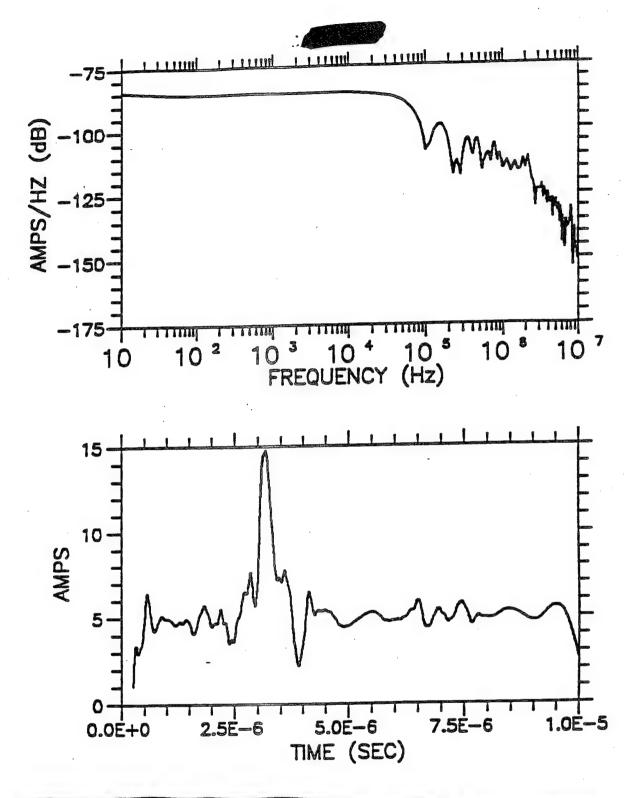


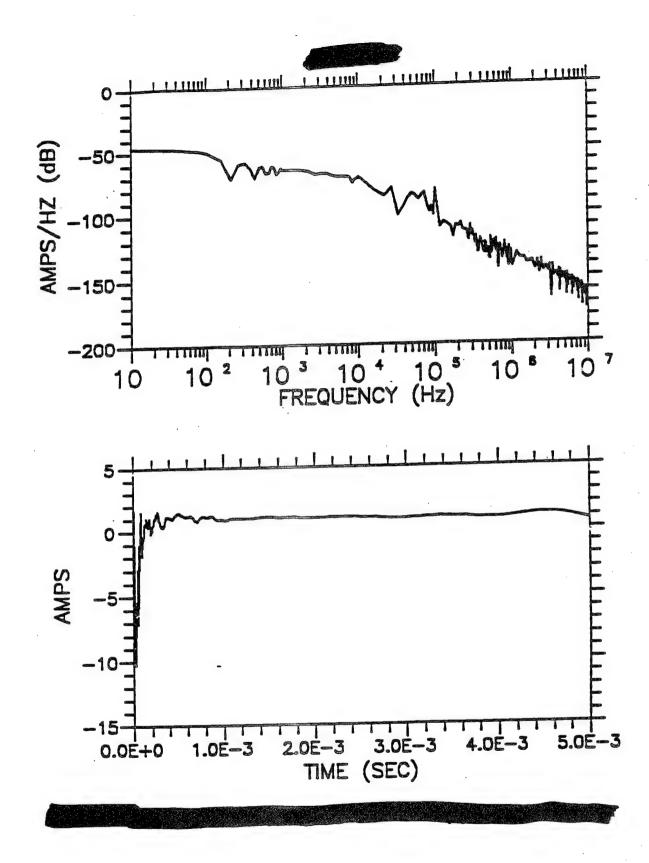


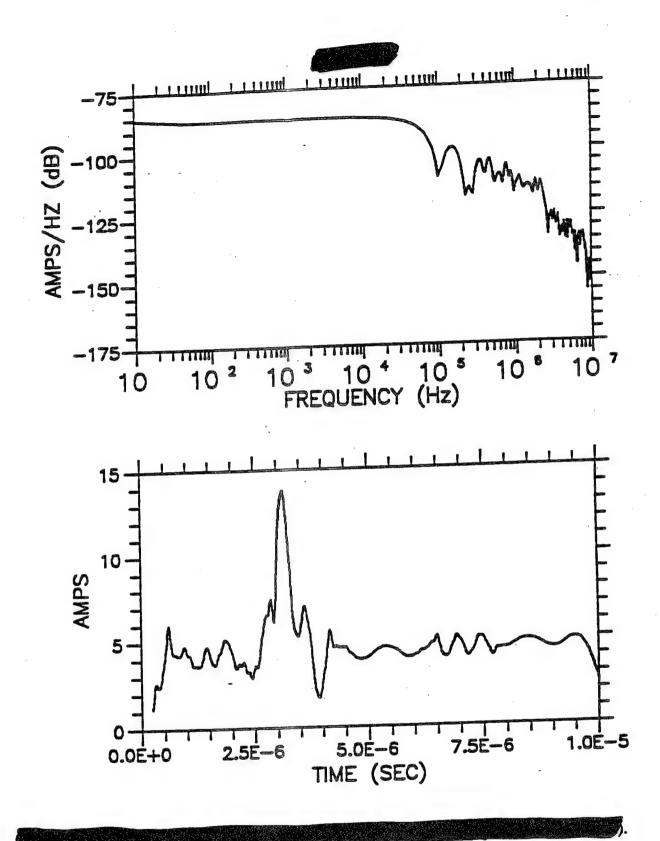


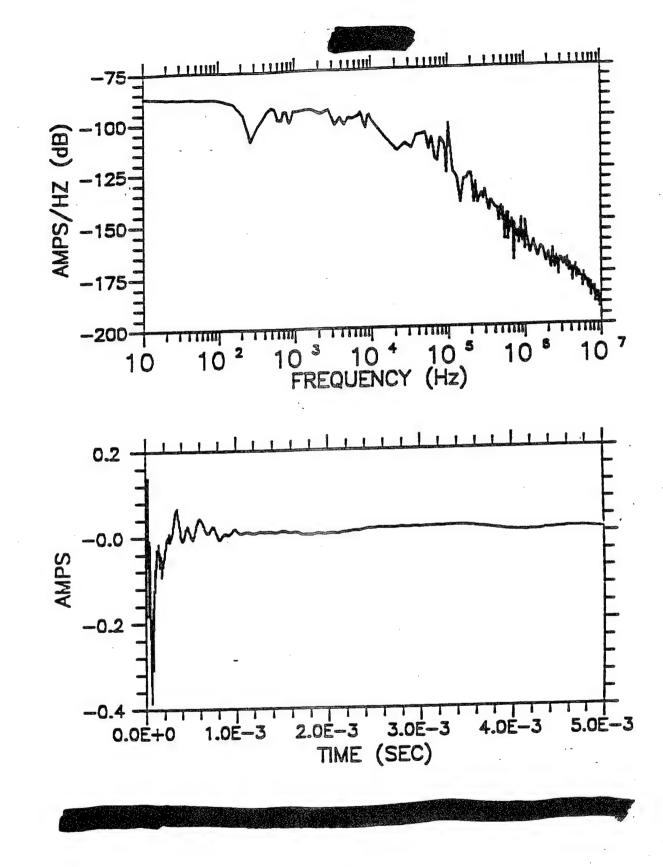


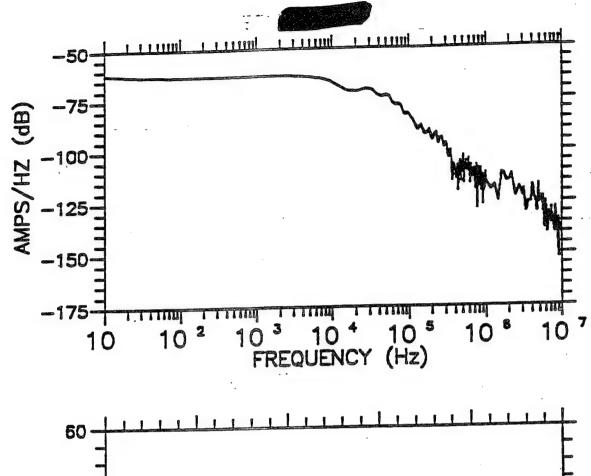


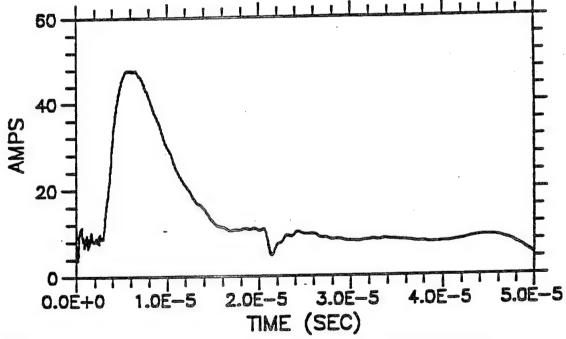


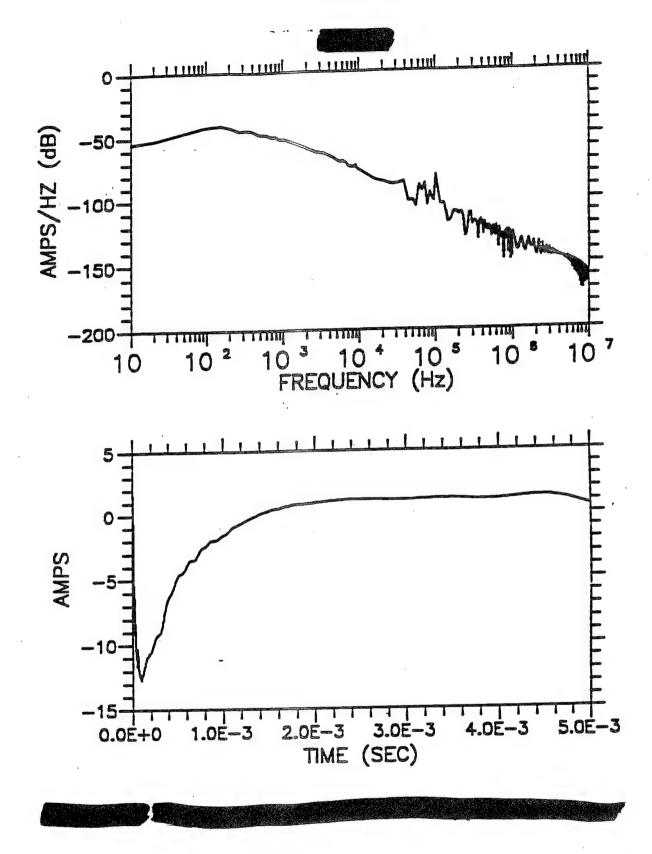


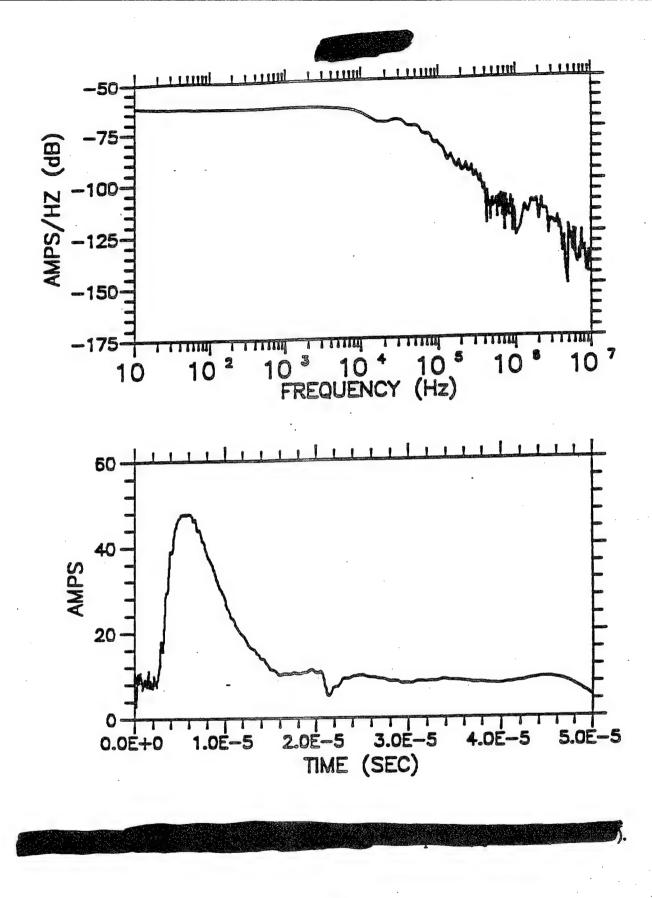


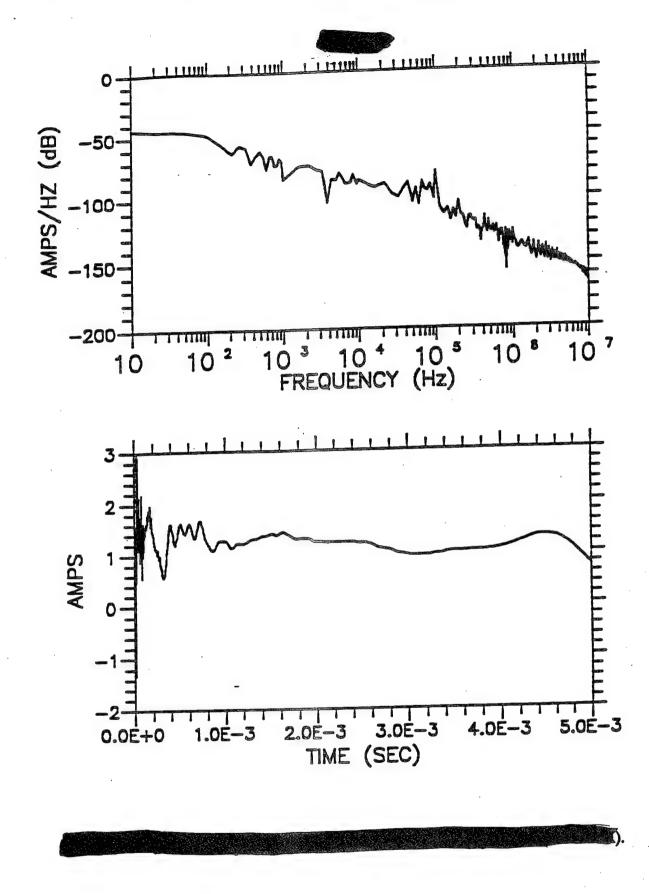


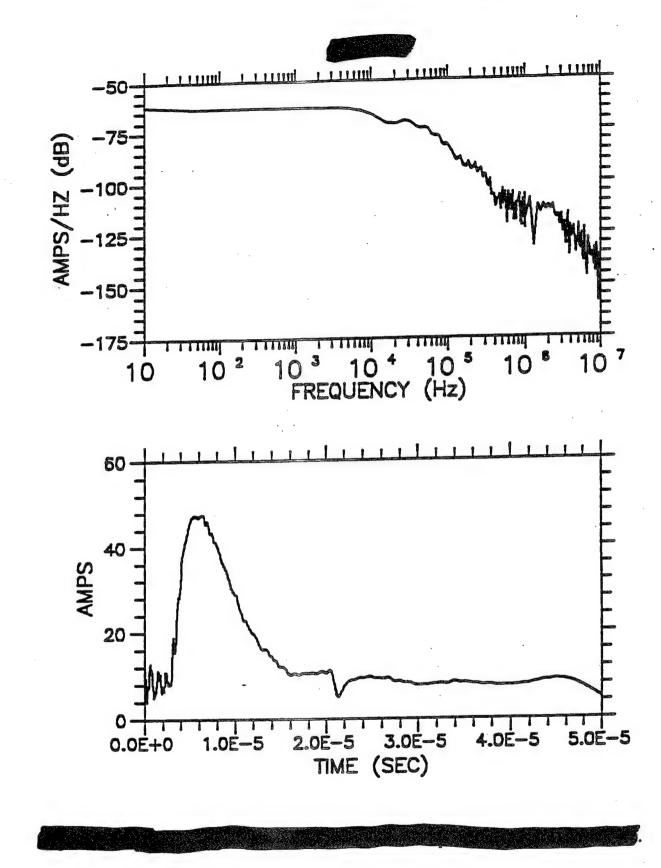


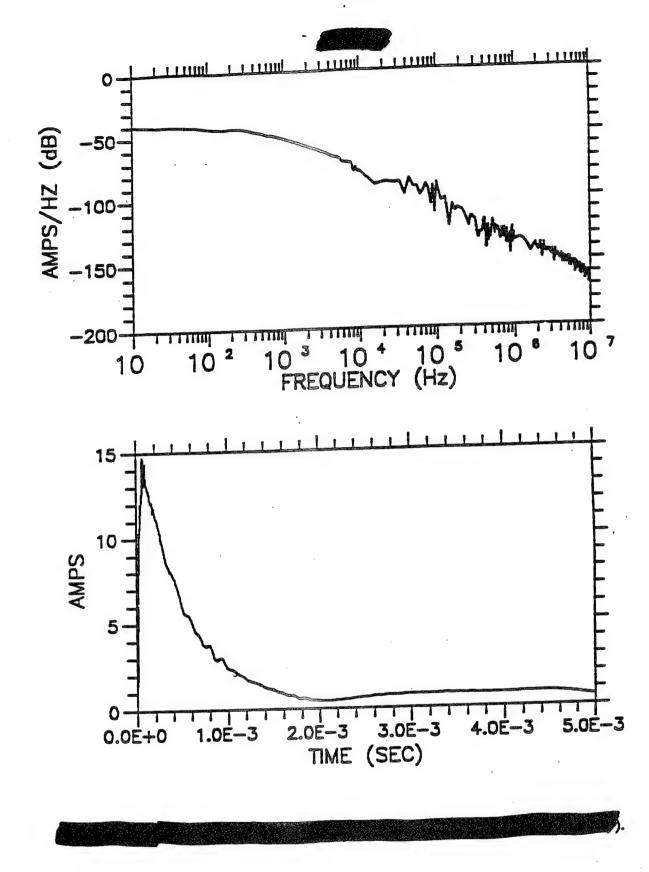


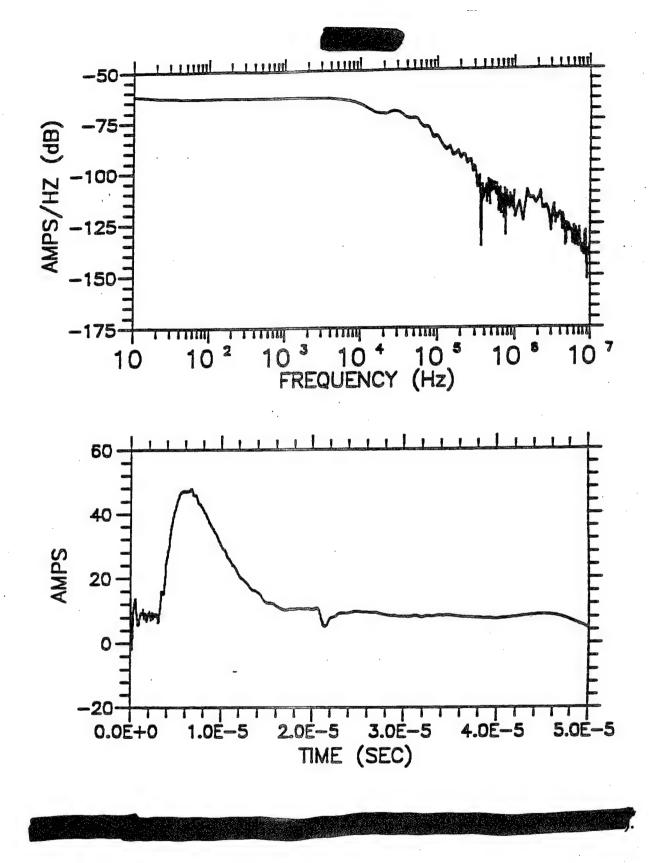


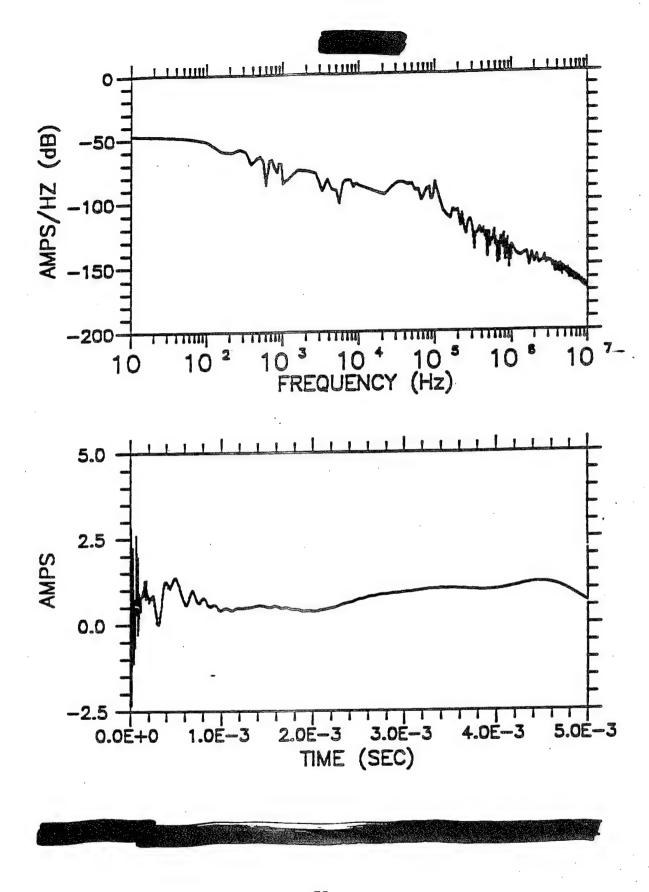












## **SECTION 4**

## HEMP COUPLING MEASUREMENTS TO ANTENNAS

## 4.1 OBJECTIVES AND OVERVIEW OF DATA ACQUIRED.

antennas were selected for CW illumination to measure the field-to-antenna transfer functions. These frequency domain measurements were then extrapolated to the HEMP environments, and inverse Fourier transformed.

From the time domain transients, the waveform descriptors (were calculated.

Table 4-1 lists the acquired measurements (files).

antennas were illuminated with a field polarized parallel to the principal radiating structure to simulate worst-case HEMP coupling. In addition, most were also illuminated with a cross-polarized field (i.e., the simulator field was perpendicular to the antenna radiating structure).

Hence, Table 4-1 indicates two measurements (I<sub>12</sub>, I<sub>20</sub>) for each illumination.

4.2 ANTENNAS TESTED.

Brief descriptions of each antenna and simulation configurations are provided in the following subsections.



CW illumination measurements of

¥55	The spiritual and the spiritual spir		to the scientific and the scientific		and the second s	বা	
Peak Error (dB)		N		2			
Inside CWMS volume	yes	yes	yes	yes	yes	yes	
B ·							
				·	9		
Peak (A)	2880	1320	839	304	250	25	
F(R <sub>a</sub> )/F(R <sub>1</sub> )	HRI		HR1	HE.	HRS	HRS	
R,(x,y,z)	E,(133,-3,13)	E,(133,-3,13)	E,(133,-3,13)	E,(133,-3,13)	E <sub>7</sub> (79,8,13)	E,(79,8,13)	
R <sub>s</sub> (x,y,z)	H,(45,0,1)	H <sub>2</sub> (45,0,1)	H,(45,0,1)	H,(45,0,1)	H,(22,2,1)	H,(22,2,1)	
load (ohms)	0	S	0	20	0	50	
Polar.	worst ' case	Worst	perp.	perp.	perp.	perp.	
File	H011	F 212	H021	H022	H051	H052	
Antenna							
No.					N		

77

antennas. (Continued) Table 4-1. CW illumination measurements of

	Commence of the Commence		pargentis la participat de conse a les	agen out actionally	الواسلامية فخير متناصيب	or other with the sector
Peak Error (dB)		۲×		ເດ		
Inside CWMS volume	yes	yes	уөз	yes	5	9
Peak (A)	372	180	47	10	60	N
F(R <sub>a</sub> )/F(R <sub>i</sub> ) file	HR5	HRS	VR9C	VR9C	HR9	HR9
R,(x,y,z)	E,(79,8,13)	E,(79,8,13)	E,(54,0,13)	E,(54,0,13)	H,(41,-35,1) E,(41,-35,13)	H,(41,-35,1) E,(41,-35,13)
R <sub>o</sub> (x,y,z)	H,(22,2,1)	H <sub>2</sub> (22,2,1)	H,(54,0,1)	H,(54,0,1)	H,(41,-35,1)	H,(41,-35,1)
load (ohms)	0	20	0	50	0	50
Polar.	perp.	perp.	worst	worat case	perp.	perp.
File	H061	H062	VO91A	V092A	H091	H092
Antenna						
o S	60		প			

antennas. (Continued) CW illumination measurements of Table 4-1.

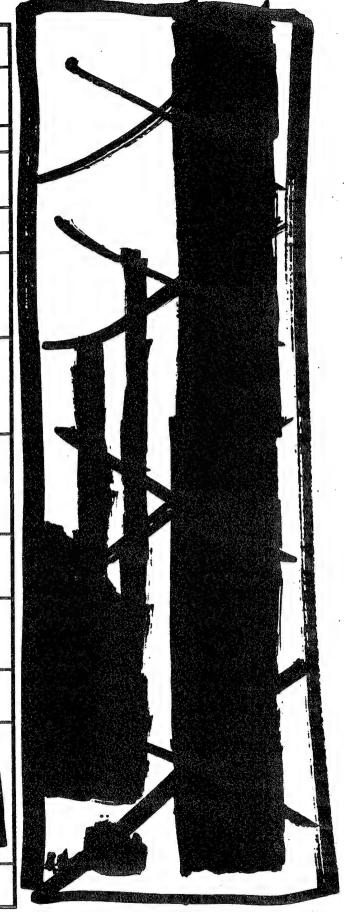
Peak Error (dB)	ate A.s.	2	net com a section of personal feet	er og fræmte fargaret.		Ŋ		-
Inside Cwms volume	уез	yes	no	90	yes	yes	ou	по
Peak (A)	25	12	-	ഗ	52	8	30	21
F(R <sub>a</sub> )/F(R <sub>i</sub> )	VR9C	VR9C	HR9	EH3	VR9C	VR9C	HR9	HR9
R,(x,y,z)	E <sub>2</sub> (54,0,13)	E,(54,0,13)	E,(41,-35,13)	E,(41,-35,13)	E,(54,0,13)	E,(54,0,13)	E,(41,-35,13)	E,(41,-35,13)
R <sub>o</sub> (x,y,z)	H,(54,0,1)	H,(54,0,1)	H <sub>2</sub> (41,-35,1)	H.(41,-35,1)	H <sub>y</sub> (54,0,1)	H,(54,0,1)	H,(41,-35,1)	H,(41,-35,1)
load (ohms)	0	50	0	20	0	50	0	20
Polar.	worst	worst , case	perp.	регр.	worst	worst case	perp.	perp.
File	V101	V102	H101	H102	711	V112	H	H112
Antenna					=			
Š								

antennas. (Continued) Table 4-1. CW illumination measurements of

Peak Error (dB)		60	- manufactum entre (	n		2		0
Inside CWMS volume	OU	5	yes	yes	no	no	yes	уев
Peak (A)	827	472	191	156	2320	1370	711	405
F(R <sub>a</sub> )/F(R <sub>1</sub> )	live ref.	live ref.	VR3	VR3	FLDCHKI	FLDCHK1	VR4	VR4
R,(x,y,z)	E,(43,66,13)	E,(43,86,13)	E,(79,0,13)	E <sub>1</sub> (79,0,13)	E,(28,-50,13)	E,(28,-50,13)	E,(57,0,13)	E,(57,0,13)
R <sub>o</sub> (x,y,z)			H,(63,0,1)	H,(63,0,1)	H <sub>4</sub> (11,-19,1)	H <sub>4</sub> (11,-19,1)	H,(22,0,1)	H,(22,0,1)
load (ohms)	0	50	0	8	0	20	0	20
Polar.	worst	worst	perp.	регр.	worst	worst	perp.	perp.
File	H031A	H032A	V031	V032	H041	H042	V041	V042
Antenna	Antenna							
Š		Commissional No. Co. of	mand daggerated water (1)					

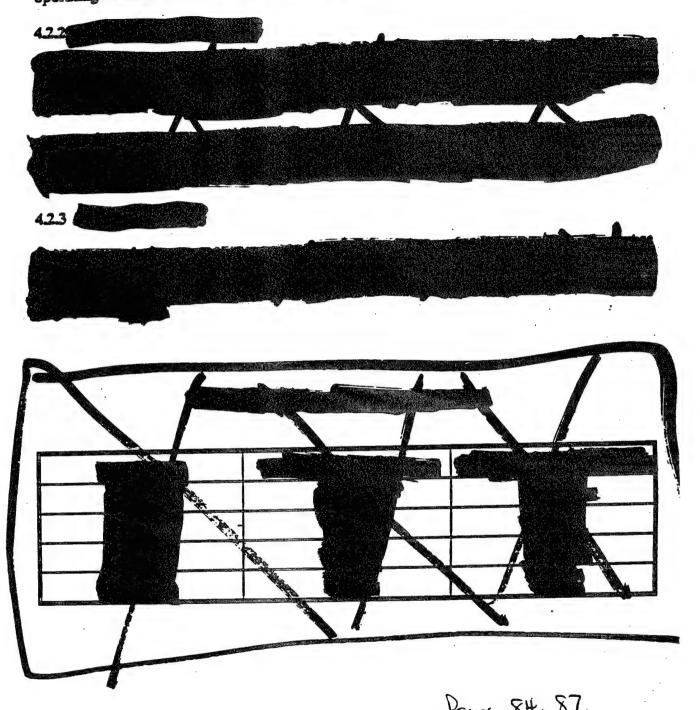
antennas. (Continued) Table 4-1. CW illumination measurements of

	a salah s	to a literal medical conference of the second
Peak Error (dB)		
inside Peak CWMS Error volume (dB)	yes	80 80 80
-	9	
Peak (A)	402	<b>96</b>
F(R,)/F(R,) Pon	VR7	VR7
A,(x,y,z)	E,(191,0,13)	E_(191,0,13)
R <sub>e</sub> (x,y,z)	H,(38,0,1)	H,(38,0,1)
load (ohms)	0	S
Polar.	worst	worst
<b>E</b>	V071	V07.2
Antenna		
è		

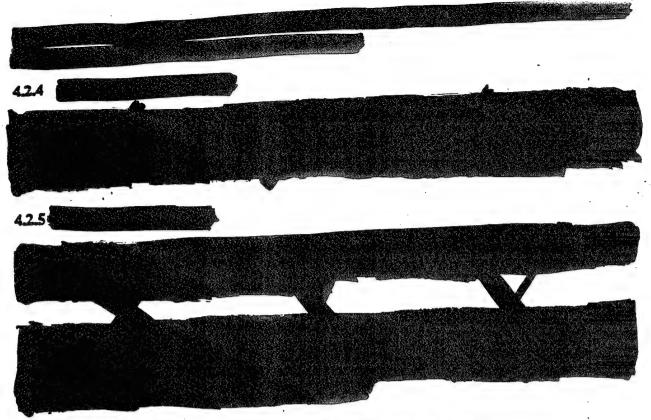


supporting tower for the CWMS drooping dipole antenna. This orientation is depicted as arrow 1 in Figure 4.2 and should provide the worst case threat (filenames H011 and H012). It is parallel to the CWMS drooping dipole depicted as arrow 2 in Figure 4-2 (filenames H021 and H022).

Operating volume of the CWMS horizontally polarized simulator.



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## 43 DESCRIPTION OF THE TESTS AND DATA PROCESSING.

## 4.3.1 Horizontally Polarized Illumination.

Test Setup: Figure 4-9 shows the CWMS simulator used to radiate horizontally polarized fields; i.e., the major electric field is parallel to the ground. The simulator uses an inverted-V dipole to radiate at discrete frequencies between 100 kHz to 102 MHz, and a logperiodic antenna from 102 MHz to 1 GHz.

Ideally, one would measure the transfer function  $I_{ANT}/E_y$ , where  $I_{ANT}$  is the current in the antenna line, and  $E_y$  is the field at the antenna location, but with the antenna removed (i.e., the undisturbed total field at the antenna location). If this transfer function could be measured, the HEMP induced current could simply be obtained by multiplying this transfer function by the  $E_y$  produced by HEMP at the same location.

In practice, the antenna cannot be "temporarily removed." To measure the undisturbed (i.e., not affected by the antenna scatter) simulation field, the field sensor is placed away from the antenna in an open area. In addition, due to test equipment constraints and the rough terrain, it was also necessary to utilize an intermediate field measurement closer to the simulator. These field measurements are referred to as "reference sensor" measurements below.

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In sum, the measurement setup was as shown in Figure 4-9. Hence, the antenna current relative to the simulator field at  $R_1$  is:

$$\frac{I_{ANT}}{E_{y}(R_{1})}(\omega) = \left[\frac{I_{ANT}}{H_{z}(R_{o})}\right] \cdot \left[\frac{H_{z}(R_{o})}{E_{y}(R_{1})}\right] \qquad (A \cdot m/V)$$
(4-1)

where the quantities in the square brackets indicate measurements. The first measurement is the antenna current relative to the magnetic field at  $R_0$ , and the second is the electric field at  $R_1$ ; i.e., closest to the antenna, relative to the magnetic field at  $R_0$ . Since the magnetic field cancels out (in theory and in practice), the antenna current relative to  $E_1$  at  $R_1$  is obtained. The reference locations  $R_0$  and  $R_1$  are identified in Table 4-1 for each measurement.

Processing: To calculate the antenna response due to a HEMP, the transfer function in Equation (4-1) is extrapolated; i.e., it is multiplied by the electric field strength which a HEMP would produce at  $R_1$ . The denominator of the transfer function is the total (incident plus reflected off the ground) electric field at 13 m above ground. Since the extrapolation function must be consistent with the simulation, we need to calculate the total HEMP field at that location per Appendix A. Thus, the extrapolated current is

$$I_{ANT}^{HEMP}(\omega) = \frac{I_{ANT}}{E_y(R_1)} \cdot E_y^{issc,HEMP}(\omega) \left[ 1 + R_H e^{-j\alpha} \right] \qquad (A/Hz)$$
 (4-2)

where  $R_H$  and  $\alpha$  are from Appendix B. The incident field  $E_y^{isc, HEMP}$  is the unclassified HEMP waveform EMP-1 defined by Reference 10:

$$E_{EMP-1}^{inc}(t) = 6.425E4 \left(e^{-at} - e^{-bt}\right) \qquad (V/m)$$

$$a = 3.00E7 \text{ sec}^{-1}, b = 4.76E8 \text{ sec}^{-1}$$
(4-3)

The result is the frequency spectrum of the antenna current due to a HEMP, and the current transient is obtained by taking the Fourier inverse transform:

$$i_{ANT}^{HEMP}(t) = \frac{1}{\pi} \int_{\omega_L} I_{ANT}^{HEMP}(\omega) e^{i\omega t} d\omega$$
 (4-4)

With two exceptions,<sup>1</sup> the antenna currents measured with the horizontal illumination field were processed accordingly. The results are contained in Appendix C. In addition, the ambient noise was measured at several antennas. Comparison plots of CWMS signal measured vs. ambient noise are included in Appendix D.

### 4.3.2 Vertically Polarized Illumination.

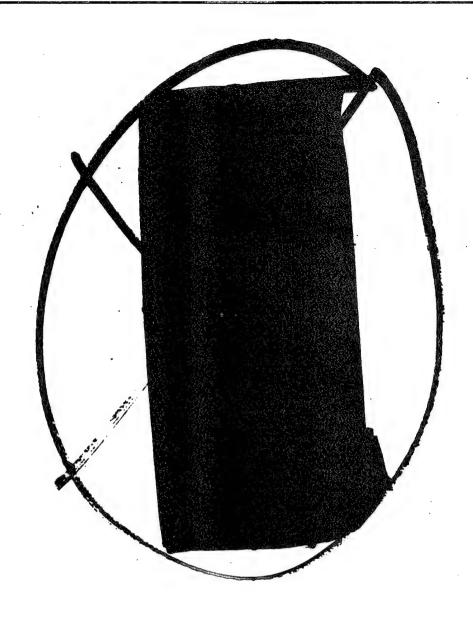
Test Setup: Figure 4-10 shows the CWMS simulator used to radiate vertically polarized fields; i.e., the major electric field is perpendicular to the ground. The simulator uses a monopole fed on the ground to radiate at frequencies between 100 kHz to 102 MHz, and a vertical logperiodic on top of the monopole at frequencies up to 1 GHz. Hence, the radiation source for the low frequency simulation is near the ground, while the radiation source above 102 MHz is about 21 m above the ground (the logperiodic antenna is mounted on top of the monopole structure). The consequences of this inconsistency are discussed below.

For the reasons discussed in the previous section, two reference (field) sensors were employed. The antenna current relative to the vertical electric field at  $R_1$  is:

$$\frac{I_{ANT}}{E_z(R_1)}(\omega) = \left[\frac{I_{ANT}}{H_y(R_o)}\right] \cdot \left[\frac{H_y(R_o)}{E_z(R_1)}\right] \qquad (A \cdot m/V)$$
 (4-5)

where the quantities in the square brackets indicate measurements. The first measurement is the antenna current relative to the magnetic field at  $R_0$ , and the second is the electric field at  $R_1$ ; i.e., closest to the antenna, relative to the magnetic field at  $R_0$ . Since the magnetic field cancels out, the antenna current relative to  $E_2$  at  $R_1$  is obtained. The reference locations  $R_0$  and  $R_1$  are identified in Table 4-1 for each measurement.

<sup>&</sup>lt;sup>1</sup>The only exceptions are files H031A and H032A, where the antenna currents were directly measured relative to the horizontal electric field at R<sub>1</sub>. This is indicated in Table 4-1 by the comment "live ref."





Processing: To calculate the antenna response due to a HEMP, the transfer function in Equation (4-5) is extrapolated; i.e., it is multiplied by the electric field strength which a HEMP would produce at  $R_1$ . As before, the extrapolation function must be consistent with the reference field (i.e., the denominator of Equation (4-5)). Since the simulator has two different source locations, we must consider two cases:

100 kHz to 102 MHz. The radiating element is a monopole above a lossy ground. If the ground were a good conductor, the simulator would be electromagnetically equivalent (by image theory) to a dipole in free space; i.e., the radiated fields would be purely incident fields. Since the ground is a moderate conductor, the fields are incident fields, modified by a correction term to account for the finite earth conductivity. For the present purposes, the correction term is neglected; and, hence, the extrapolation is:

$$I^{HEMP}(\omega) = \frac{I_{ANT}}{E_z(R_1)} \cdot E_z^{\text{sec, HEMP}}(\omega) \qquad (A/Hz)$$
 (4-6)

As before, the unclassified waveform EMP-1 is used for  $E_z^{\text{tec}, \text{HEMP}}$ 

102 MHz to 1 GHz: The radiating element is a logperiodic antenna, roughly 21 m above ground. It produces a total field (incident plus reflected off the ground) at the reference sensor at R<sub>1</sub>. Accordingly, the extrapolation function (from Appendix A) is:

$$E_z^{\text{inc. HEMP}}$$
 ( $\omega$ )  $\left[1+R_{\chi}e^{-\beta z}\right] \approx E_z^{\text{inc. HEMP}} \left(\frac{V/m}{Hz}\right)$  (4-7)

The approximation follows from Appendix B which shows that  $R_V$  is much smaller than unity; hence, the extrapolation function in Equation (4-6) can be also be used at high frequencies.

The resulting frequency spectra for the HEMP induced antenna currents, and the inverse Fourier transforms are presented in Appendix C.

### 4.4 HEMP INDUCED ANTENNA CURRENTS.

All measurements were processed as described in Section 4-2, and are contained in Appendix C. The results are summarized in Table 4-1 of Section 4-1.

d. The file name indicates whether the horizontal CWMS simulator was used (prefix "H"), or the vertical simulator (prefix "V"). The column entitled "Polar" describes whether the simulator fields were parallel to the principal antenna radiating structure ("WORST CASE"), or perpendicular ("PERP"). The next column identifies the load on the antenna coaxial cable; i.e., whether the current was measured into 50 ohms or into a short circuit.

The column entitled "Inside CWMS Volume" indicates whether the test object (antenna) was outside the simulation volume.

The last column accounts for the fact that the reference location  $R_1$  was not at each test object as discussed in Section 4-2, but closer to the simulator. Since the simulation field strength decreases as 1/distance (cf. References 9, 11), the error is  $20 \log(d/R_1)$ , where d is the distance from the simulator to the antenna, and  $R_1$  is the distance from the simulator to the reference location  $R_1$ .

## 4.4.1 Representative Results for Each Antenna.

Table 4-1 shows that worst case polarization indeed produces the largest currents in the antennas. The currents induced in a 50 ohm test load and into a short circuit are overlaid in the following figures (Figures 4-11 to 4-19) for the worst case polarization of the incident field, except in the two cases indicated. Each figure displays the spectra and the time domain transients.

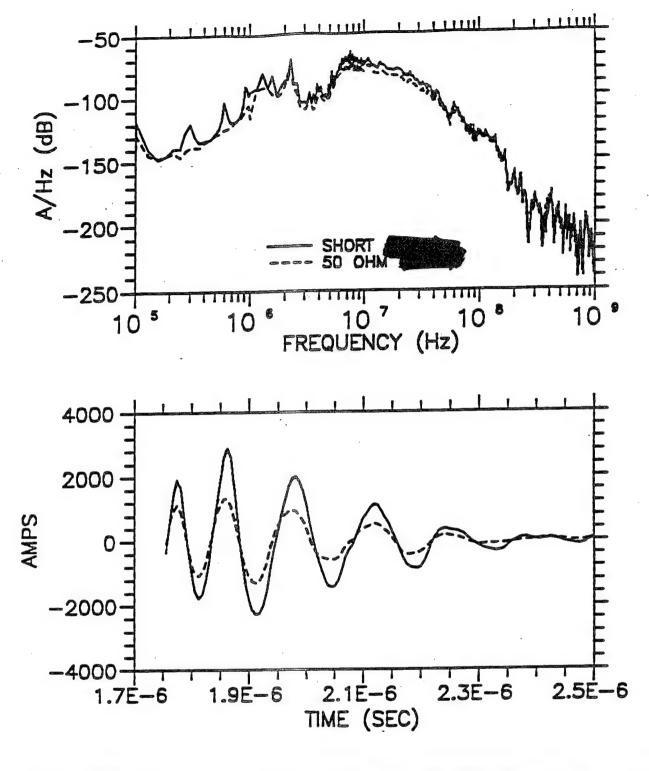
Note that the short-circuit and 50 ohm current waveforms are quite similar, i.e., the short-circuit current is about twice the current into 50 ohms. The reason for this is discussed in the next section.

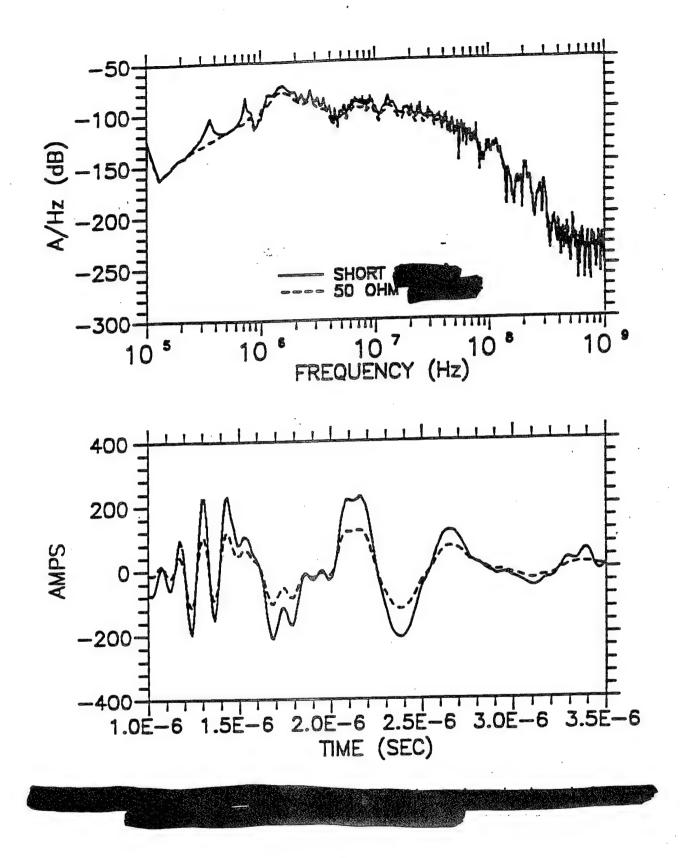
#### 4.4.2 Antenna Impedance.

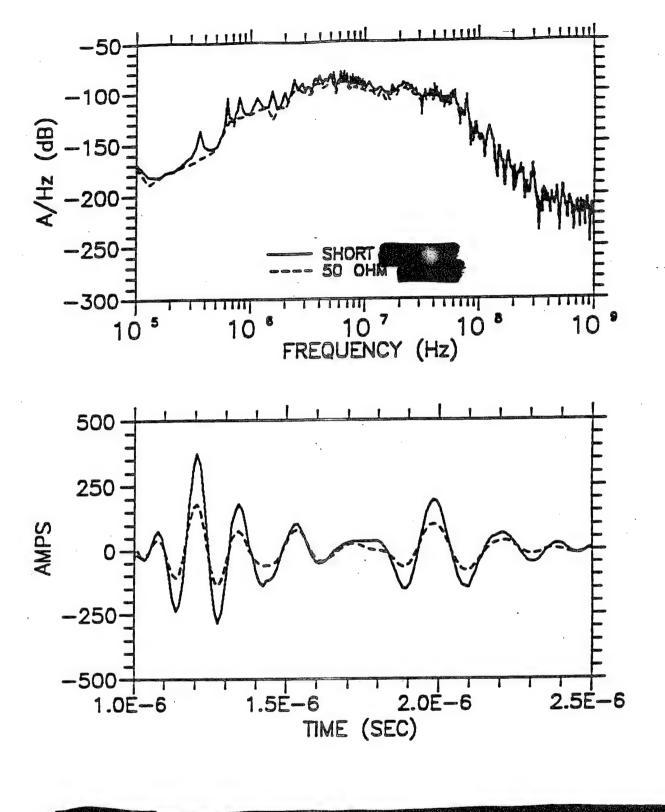
Figure 4-20 shows the electrically important elements of the coupling path from the voltage generated at the antenna terminals to the test load, and the equivalent circuit for this path. This circuit represents the HEMP stress seen by the radio equipment; hence, it is the ideal injection test simulator.

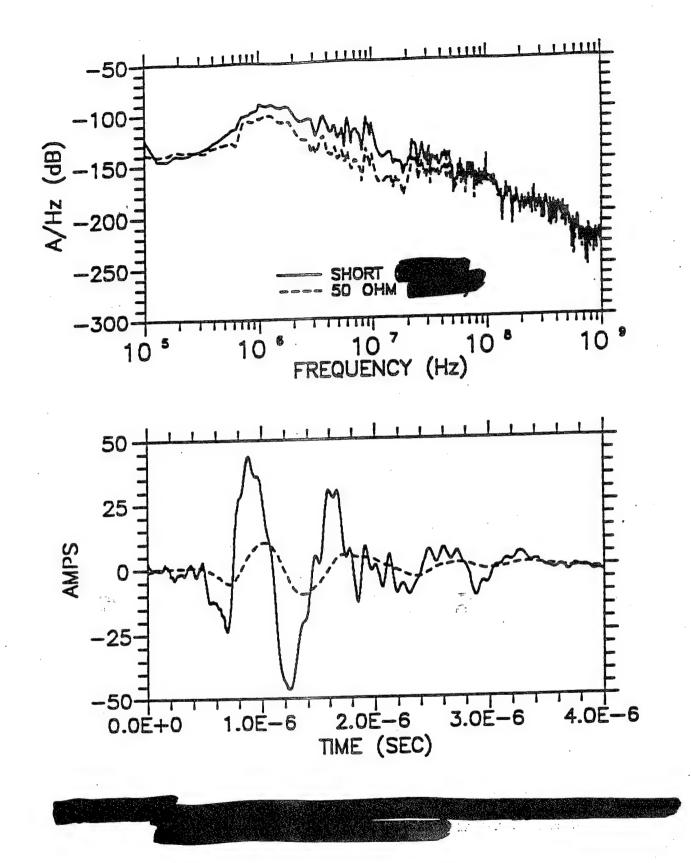
The only unknown in this circuit is the input or source impedance  $Z_m$ , which can be calculated by

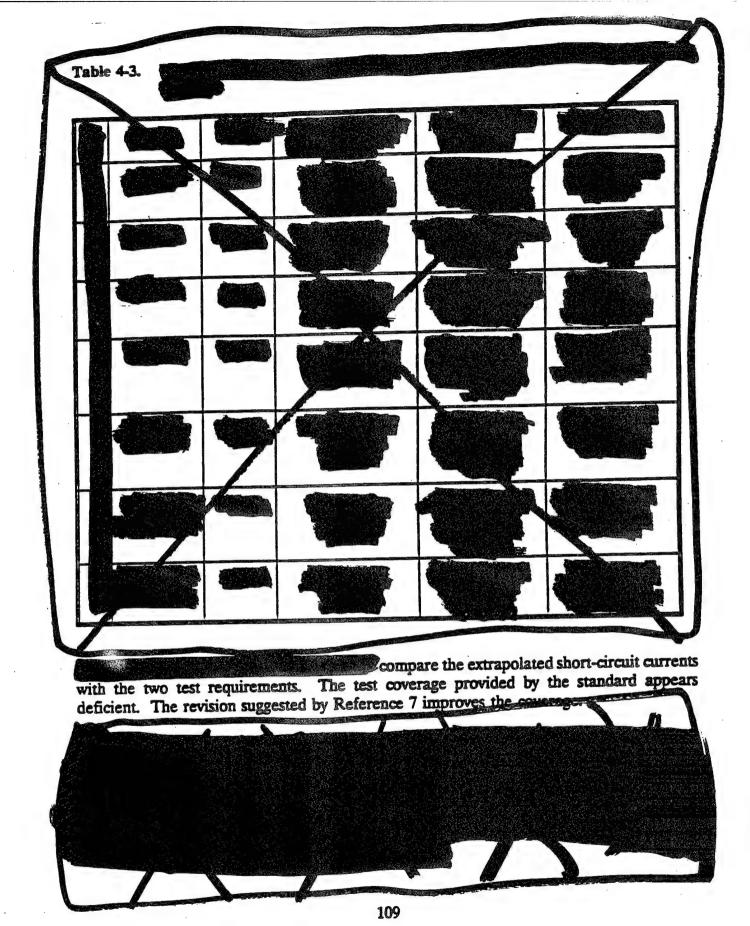
$$Z_{\rm in} = 50 \frac{I_{\rm S0}}{I_{\rm in} - I_{\rm S0}}$$
 (0)

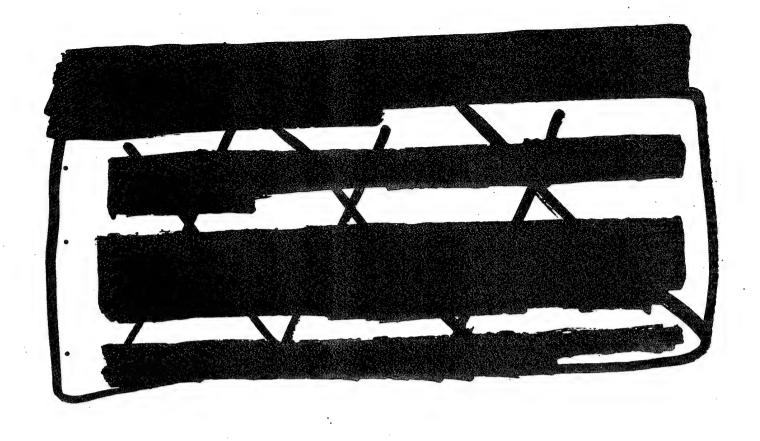


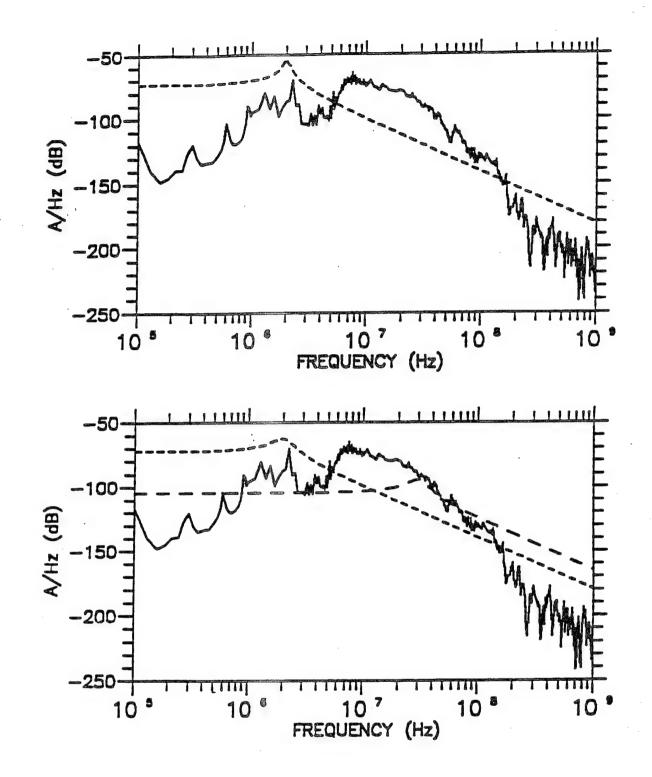


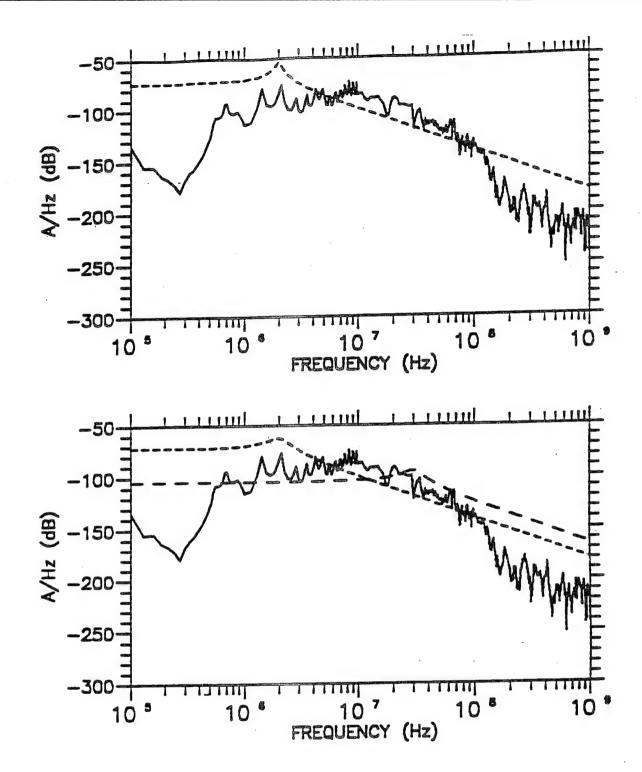


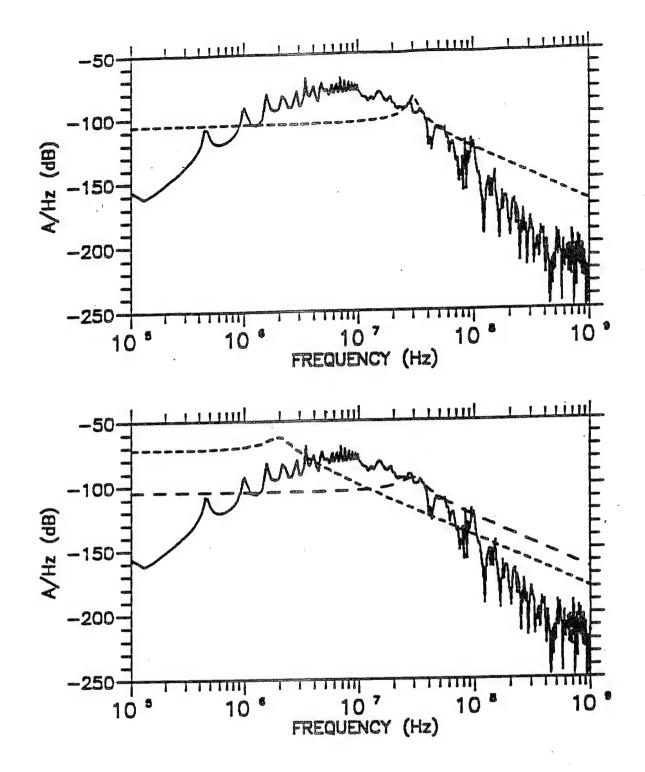




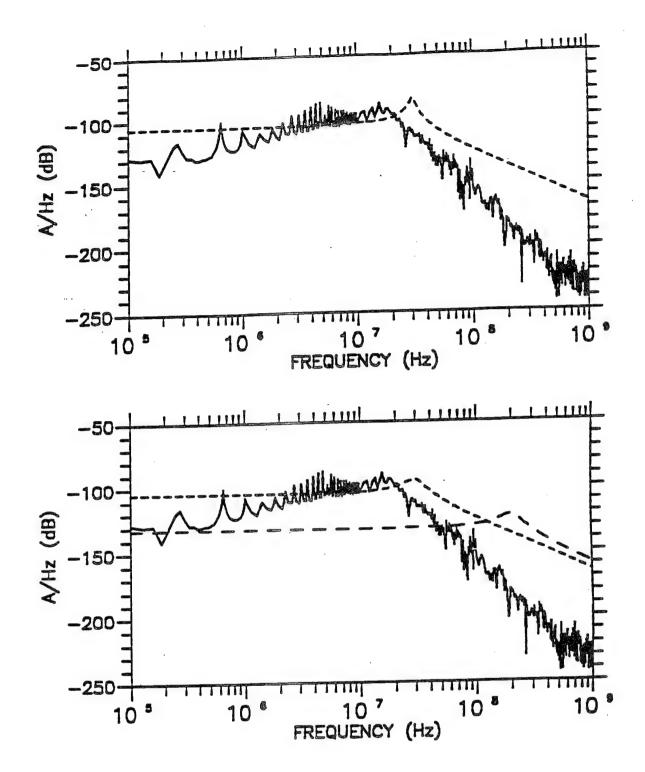


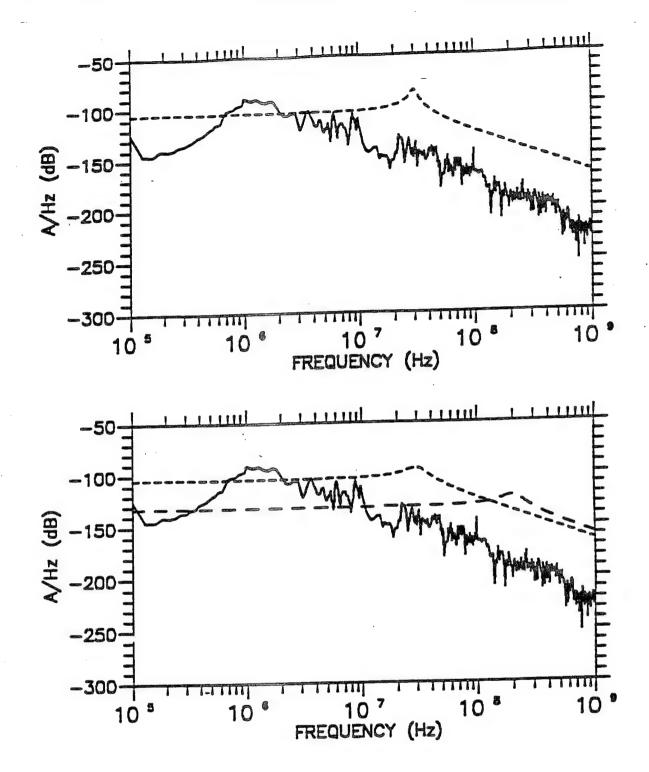




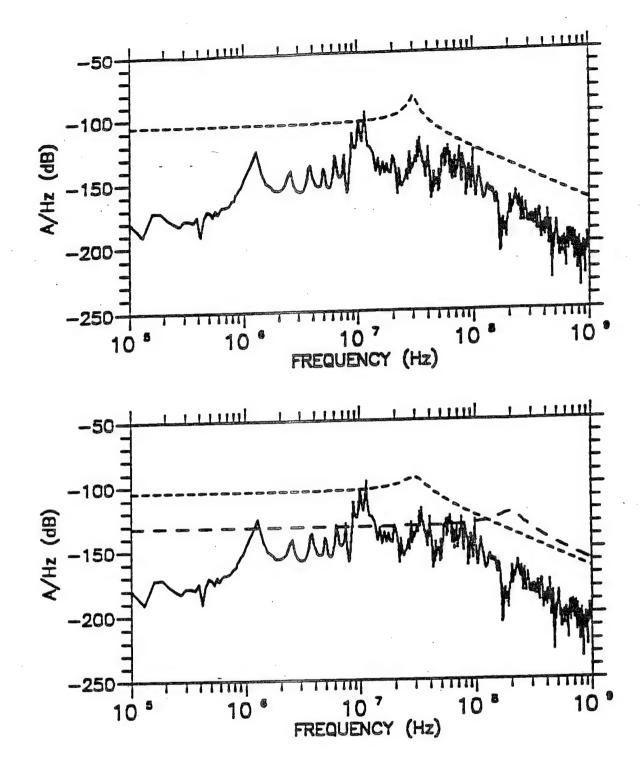


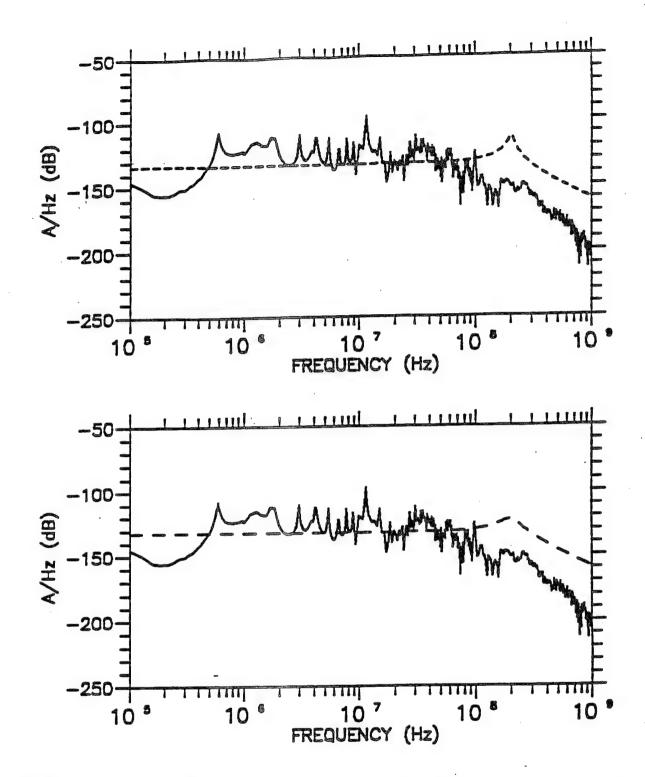










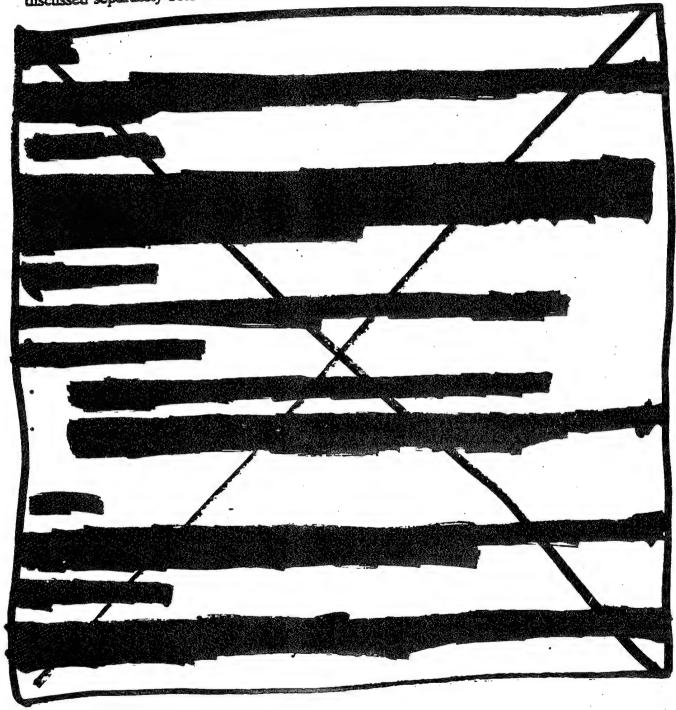


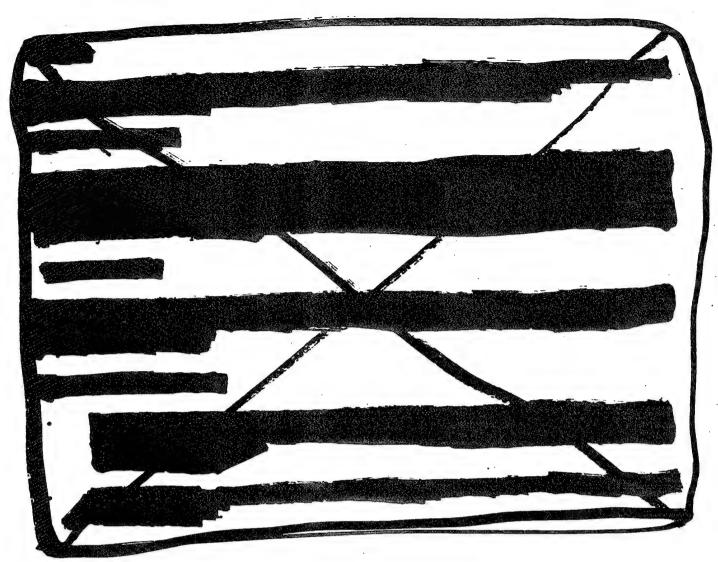


### SECTION 5

# CONCLUSIONS AND RECOMMENDATIONS

The test met all objectives. The test results provide complete answers to all issues addressed. Each issue is discussed separately below.





#### ISSUE:

What test waveforms adequately simulate HEMP stresses on test radio equipment connected to antennas?

#### **OBSERVATIONS:**

HEMP coupled stresses to antennas can be adequately simulated with damped sinusoids as suggested by MIL-STD-188-125.

The revision to the standard in Reference 7 provides better test coverage because it uses two damped sinusoids for each antenna.



The transients stressing the radio equipment can be represented by an equivalent Thevenin circuit with source impedance of 50 to 100 ohms. Observed quality factors (Q) are lower than the Q=10 required by MIL-STD-188-125.

#### CONCLUSIONS:

Neither MIL-STD-188-125 nor previously suggested revisions account for the effects of a tower.

### **RECOMMENDATIONS:**

Adopt the suggested revision in Reference 7, but add the requirement that the radio equipment must also be tested with a damped sinusoid at 2 MHz with 500 A

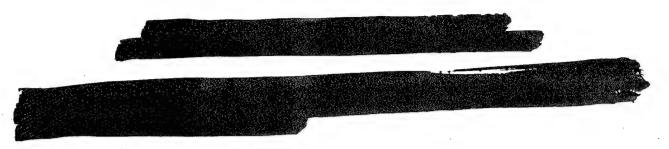
#### SECTION 6

#### REFERENCES

- 1. "Military Standard, High-Altitude Electromagnetic Pulse Protection for Ground-Based C4I Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125, 26 June 1990.
- 2. T. Zwolinski, "Test Director's Report for the HEMP Simulation Test," MRC/COS-R-1309, July 1992.
- D. Schafer, "E3 Pulser and Data Line Coupler/Isolator Acceptance Test," MRC/ABQ-R-1494, March 1992.
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- 6. B. Harlacher, "Characterization of the E2 Pulse Generator," MRC/COS-M-95-7, 3 January 1992.
- J. Lubell, "Changes to Appendix B" (of MIL-STD-188-125), Memorandum to W. Scott, Maj. R. Launstein, J. Zych, 13 March 1992.
- 8. R. Shoup, "Field Mapping Test of the DNA CW Antenna System," DNA-TR-84-168, 7 September 1983.
- 9. W. Bereuter and R. Racca, "Processing of CWMS Field Map Measurements," MRC/COS-N-131, 9 November 1987.
- 10. Classification Guide for "Advanced Fixed GBC4I Testing Program," 1 July 1989.
- 11. R. Racca and S. Dunivin, Interna Field Map Test," MRC/COS-R-1082, 5 October 1990.
- 12. R. Racca, W. Bereuter, and S. Dunivin, Antenna Test MRC/COS-N-179, 29 January 1991.

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### APPENDIX A



#### 1.0 BACKGROUND

Section 3 describes the simulated HEMP testing

rulser qualification testing indicates that the E2 pulser delivers a double exponential short-circuit current with peak amplitudes up to 500 A, rise times less than 1 µs, and durations (FWHM) of about 5 ms (Reference O

The purpose of this appendix is to describe the circuit models used to estimate the responses

2.0 CIRCUIT MODELS

The schematic in Fig. 1(a) can be reduced to an equivalent circuit shown in Fig. 1(c) using standard circuit equivalences. The first reduction reflects the 2 ohm load resistance



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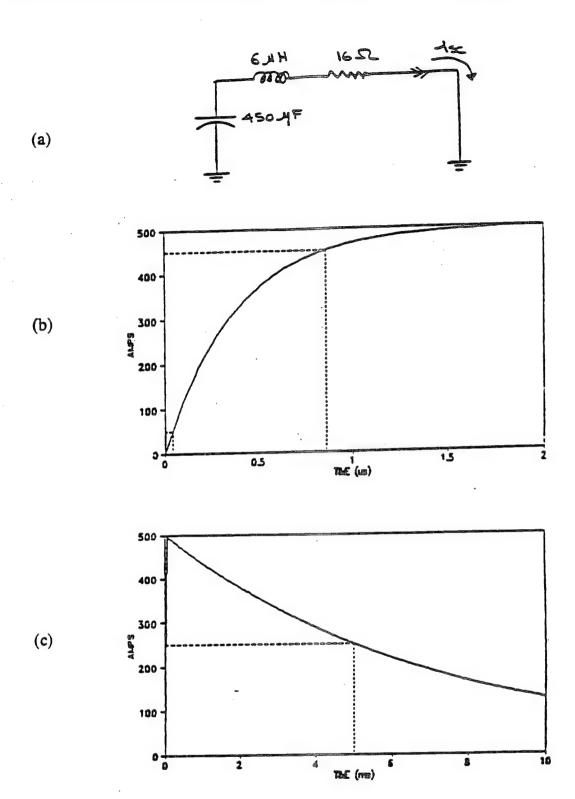


Figure 2. Circuits and responses for the E2 pulser: (a) circuit model, (b) early-time response, and (c) late-time response.

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#### APPENDIX B

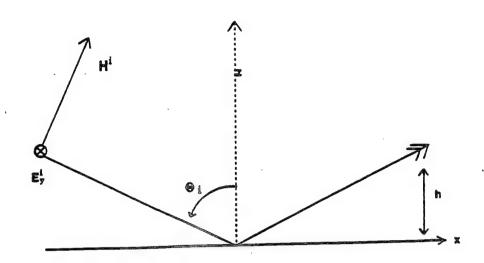
## CALCULATION OF TOTAL FIELDS

This Appendix contains the equations to calculate the total (incident plus ground reflected) fields at a height h above the ground. The equations are for a horizontally polarized plane wave (incident electric field is parallel to the ground), and for a vertically polarized plane wave (incident magnetic field is parallel to the ground). The plane waves are incident along a propagation direction which is in the xy plane and forms an angle  $\theta_i$  with the z-axis.

The angles of incidence are between 68° and 83°, depending on the antenna distance to the CWMS simulator and the height of the antenna tested. The earth parameters  $E_r$ ,  $\sigma$  were estimated by matching the calculated field transfer functions to the measured transfer functions. The estimated values are  $\varepsilon_r = 5$ , and  $\sigma = .01$  to 1 mho/m.

The approximations for small x are provided for convenience. They are valid at frequencies where the ground is a good conductor.

## HORIZONTAL POLARIZATION



$$R_{H} = \frac{\text{COS}\theta_{i} - \left[\epsilon_{r} (1+\chi) - \sin^{2}\theta_{i}\right]^{1/2}}{\text{COS}\theta_{i} + \left[\epsilon_{r} (1+\chi) - \sin^{2}\theta_{i}\right]^{1/2}} = -1+2 \text{COS}\theta_{i} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

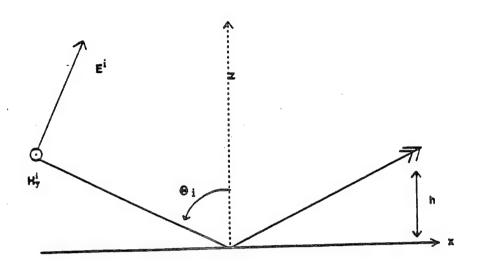
$$E_{y}^{TOT} = E_{o}(1+R_{H}e^{-j\alpha}) = 2 E_{o} \text{COS}\theta_{i} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

$$H_{z}^{TOT} = \frac{E_{o}}{\eta_{o}} \text{COS}\theta_{i} (1-R_{H}e^{-j\alpha}) = \frac{E_{o}}{\eta_{o}} 2 \text{COS}\theta_{i} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

$$H_{z}^{TOT} = \frac{E_{o} \sin\theta_{i} (1+R_{H}e^{-j\alpha})}{\eta_{o}} = \frac{E_{o}}{\eta_{o}} 2 \sin\theta_{i} \text{COS}\theta_{i} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

 $\alpha = 2k_o h \cos\theta_i$ ;  $\chi = \sigma/j\omega\epsilon$ , approx. valid for  $|\chi| > 1$ 

## VERTICAL POLARIZATION



$$R_{v} = \frac{\epsilon_{r}(1+\chi) \cos \theta_{i} - \left[\epsilon_{r}(1+\chi) - \sin^{2} \theta_{i}\right]^{1/2}}{\epsilon_{r}(1+\chi) \cos \theta_{i} + \left[\epsilon_{r}(1+\chi) - \sin^{2} \theta_{i}\right]^{1/2}} = 1 - \frac{2}{\cos \theta_{i}} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

$$E_{x}^{TOT} = E_{o} \cos \theta_{i} \left(1 - R_{v}e^{-j\alpha}\right) = E_{o}^{2} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}$$

$$E_{z}^{TOT} = E_{o}\sin \theta_{i} \left(1 + R_{v}e^{-j\alpha}\right) = E_{o}^{2} \sin \theta_{i} \left(1 - \frac{1}{\cos \theta_{i}} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}\right)$$

$$H_{y}^{TOT} = \frac{E_{o}}{\eta_{o}} \left(1 + R_{v}e^{-j\alpha}\right) = \frac{E_{o}}{\eta_{o}} 2 \left(1 - \frac{1}{\cos \theta_{i}} \sqrt{\frac{j\omega\epsilon_{o}}{\sigma}}\right)$$

 $\alpha = 2k_o h \cos \theta_i$ ;  $\chi = \sigma/j \omega \epsilon$ , approx. valid for  $|\chi| > 1$ 

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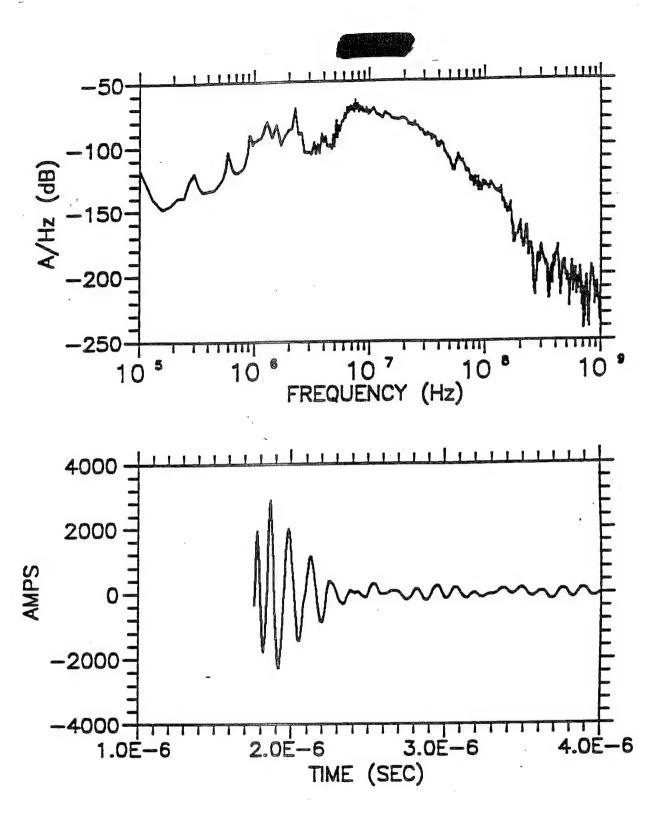
#### APPENDIX C

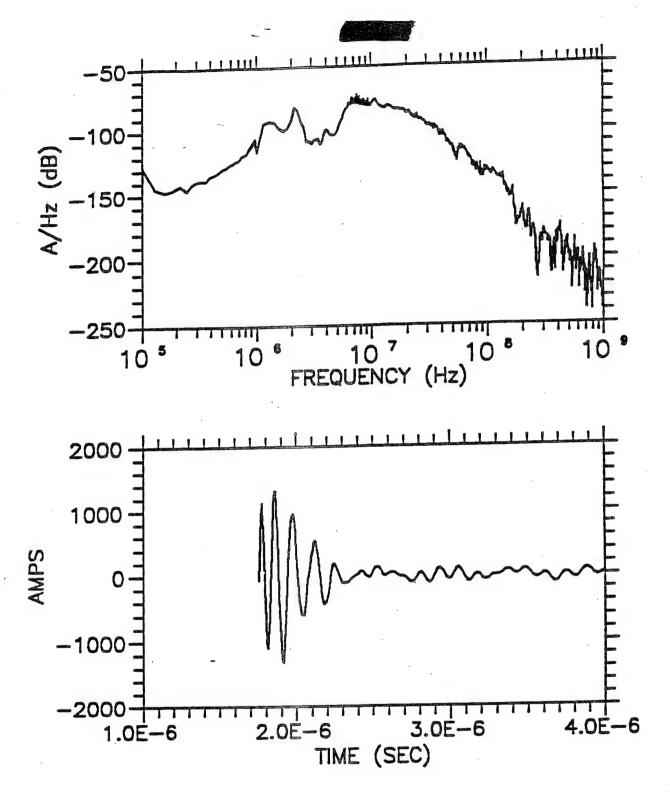
### ANTENNA CURRENTS

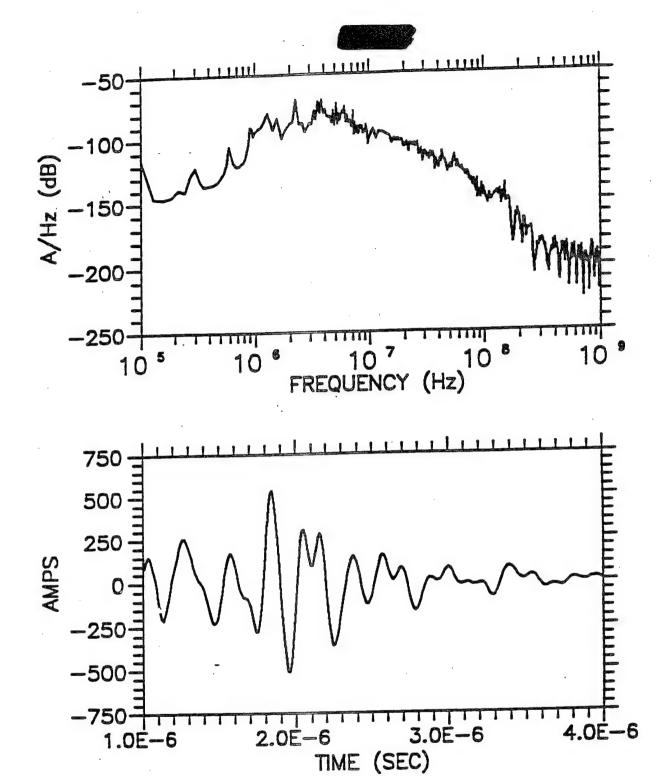
This appendix contains plots of the antenna currents measured and extrapolated to HEMP environments. Measurements with prefix "H" were extrapolated to the total electric field (cf. Section 4.3.1), and measurements with prefix "V" were extrapolated to the incident electric field (cf. Section 4.3.2).

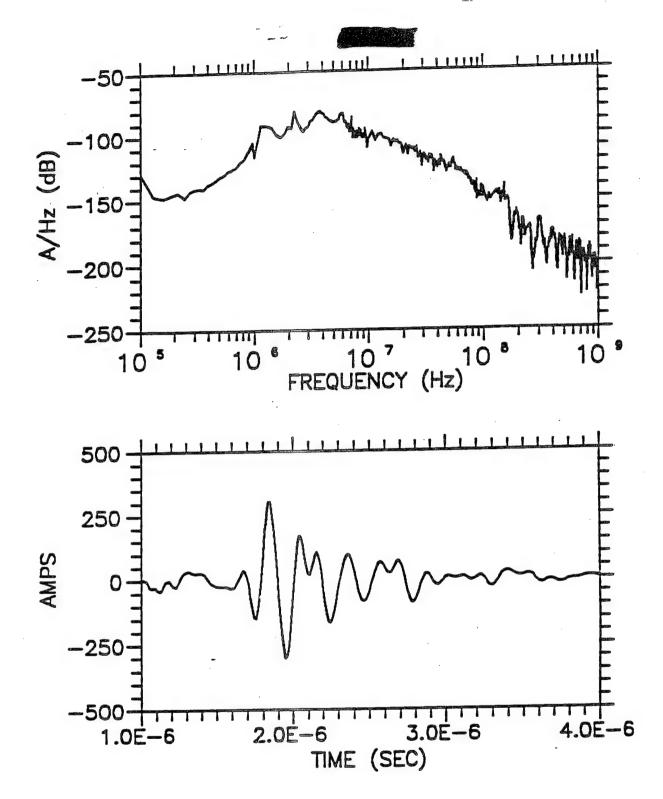
For each measurement, the frequency domain amplitude spectrum is plotted in dB = 20 log  $|I(\omega)|$ . On the same page, the inverse Fourier transform is shown.

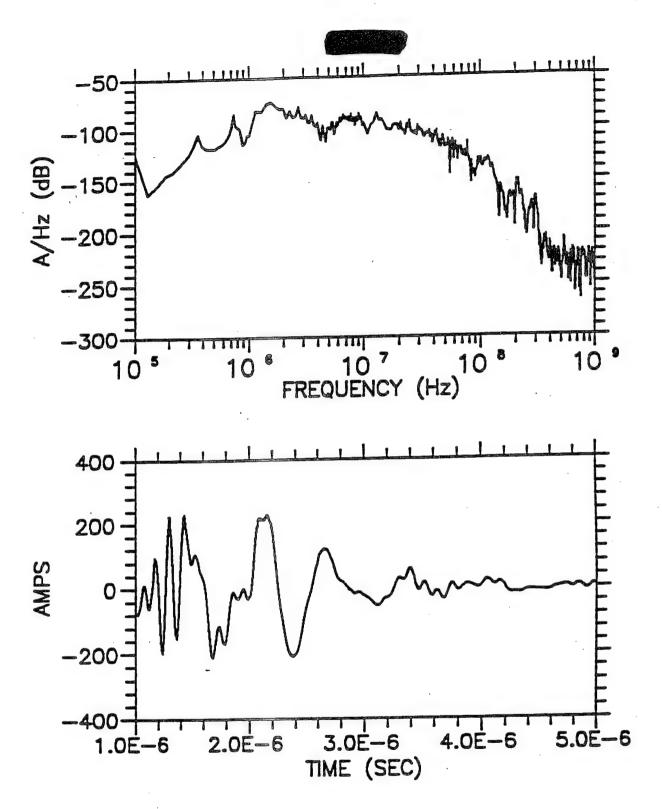


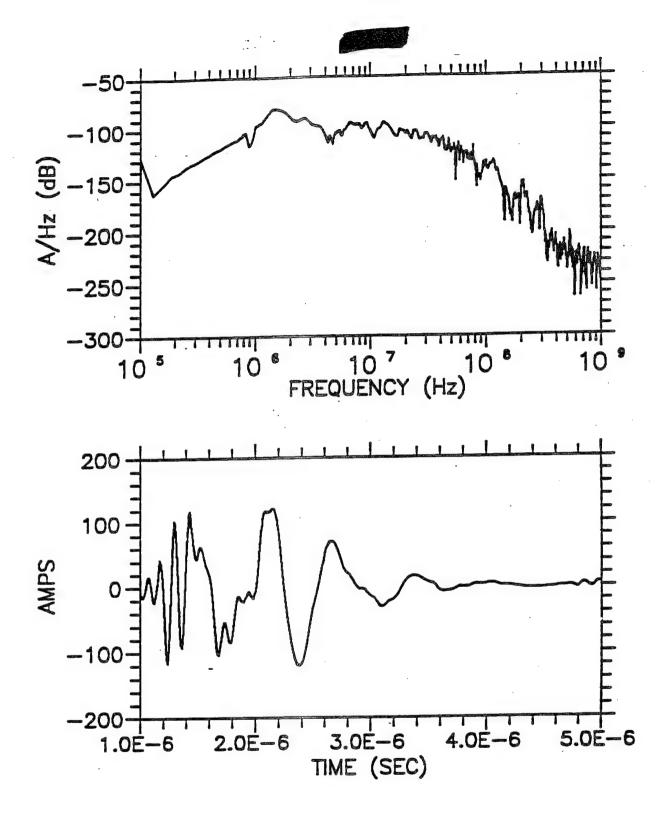


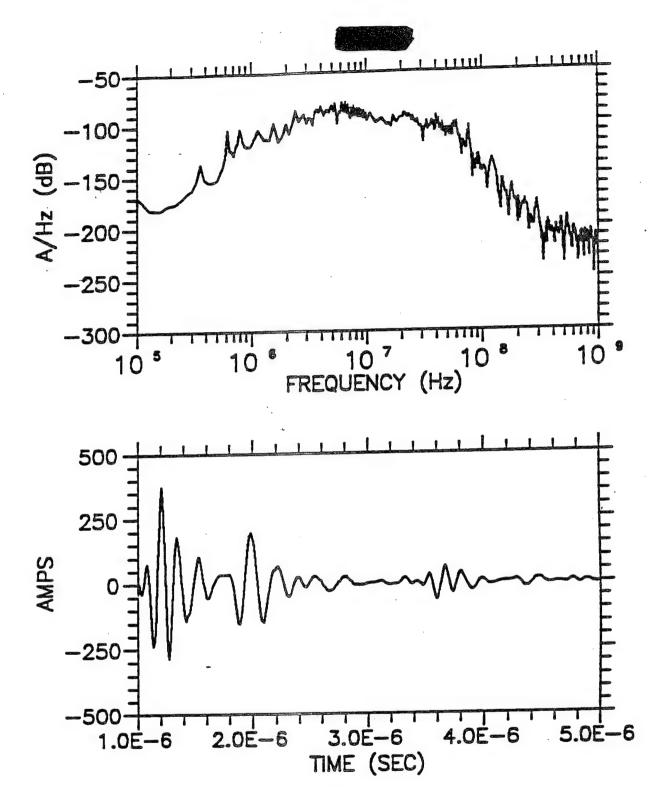


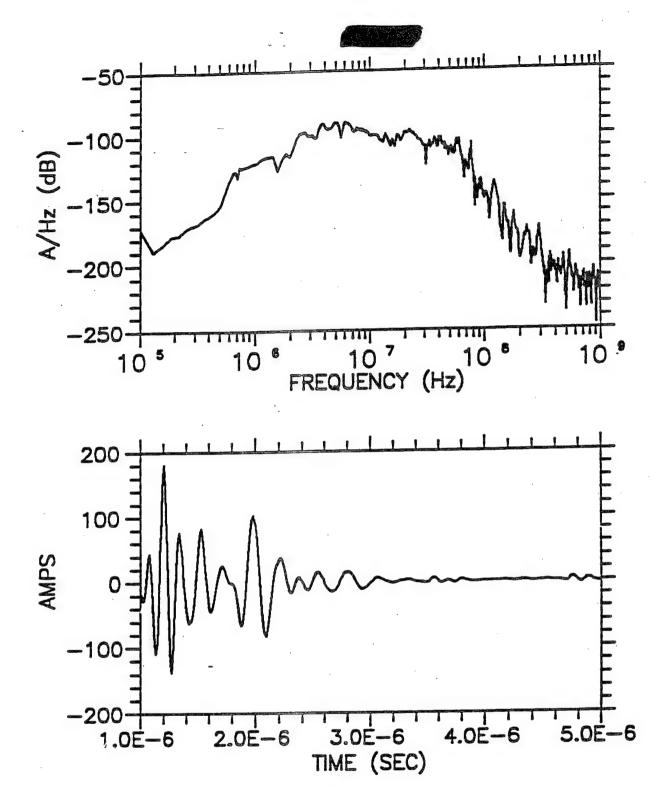


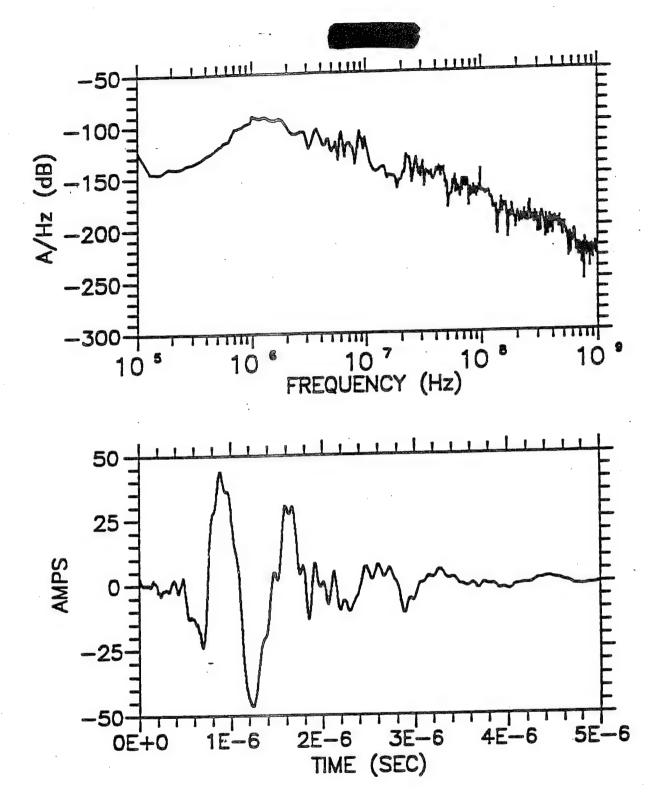


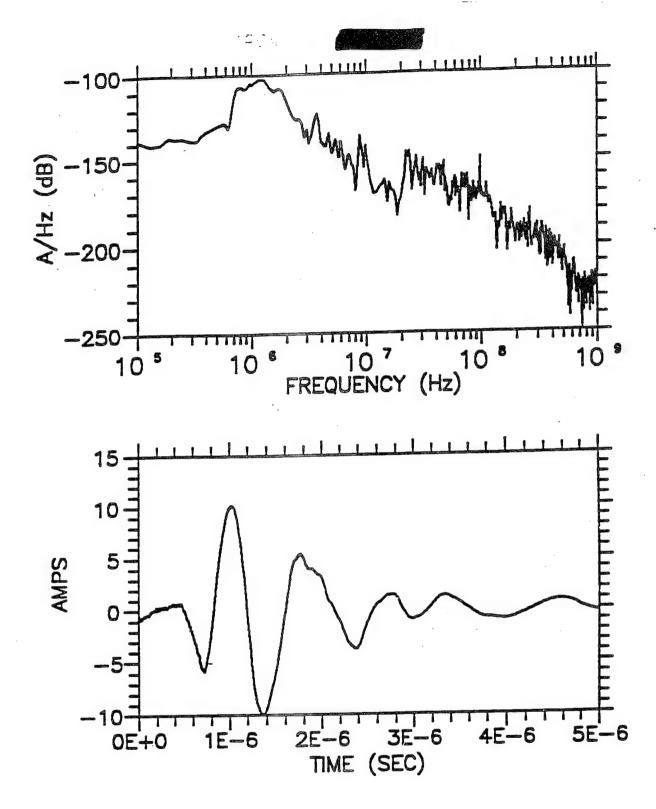


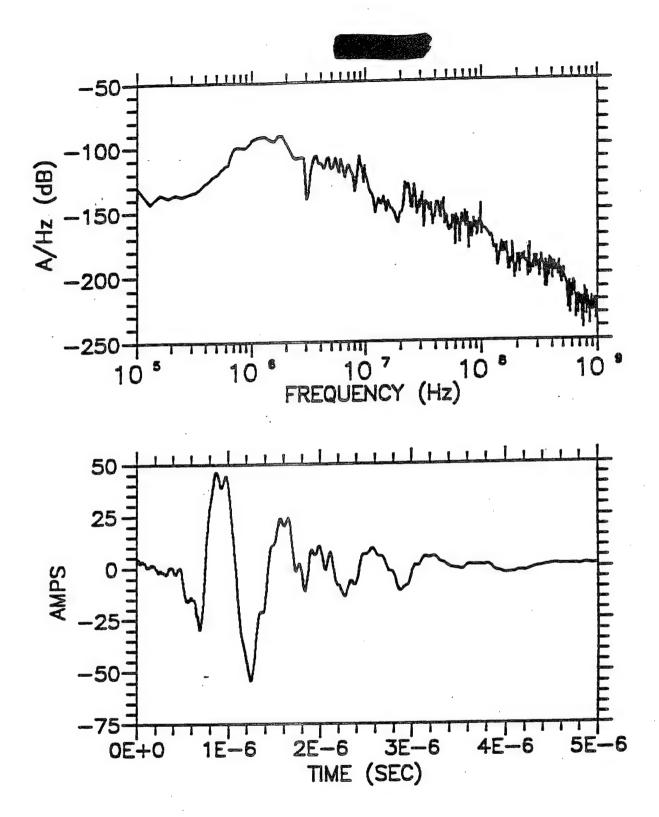


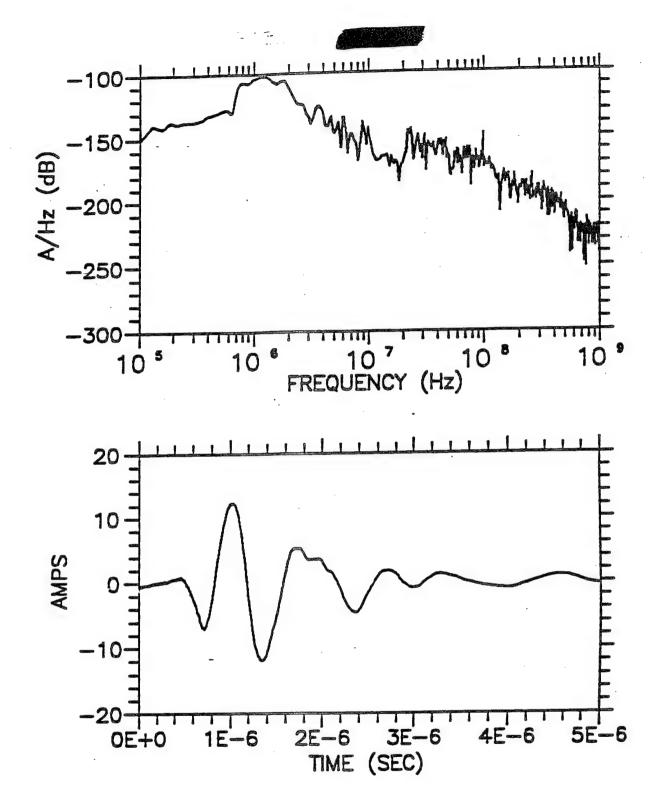


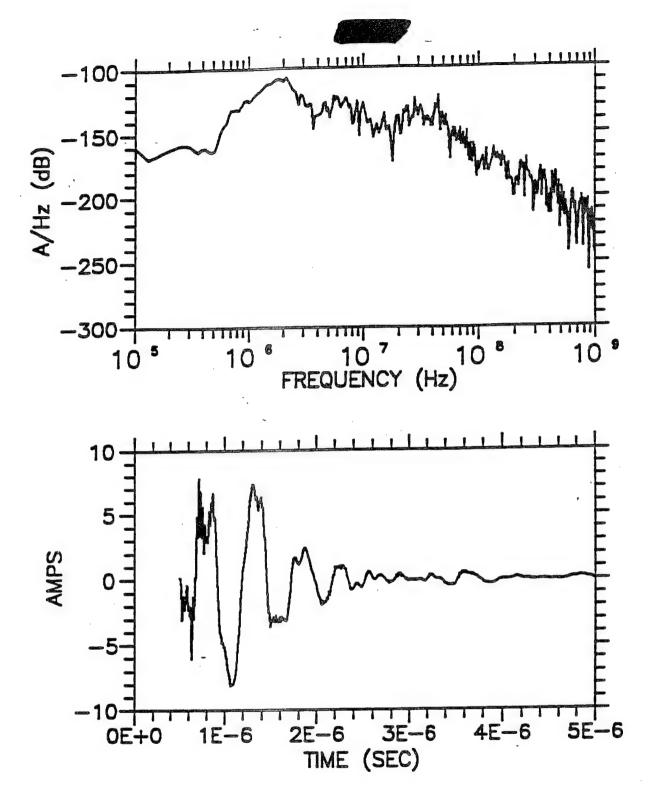


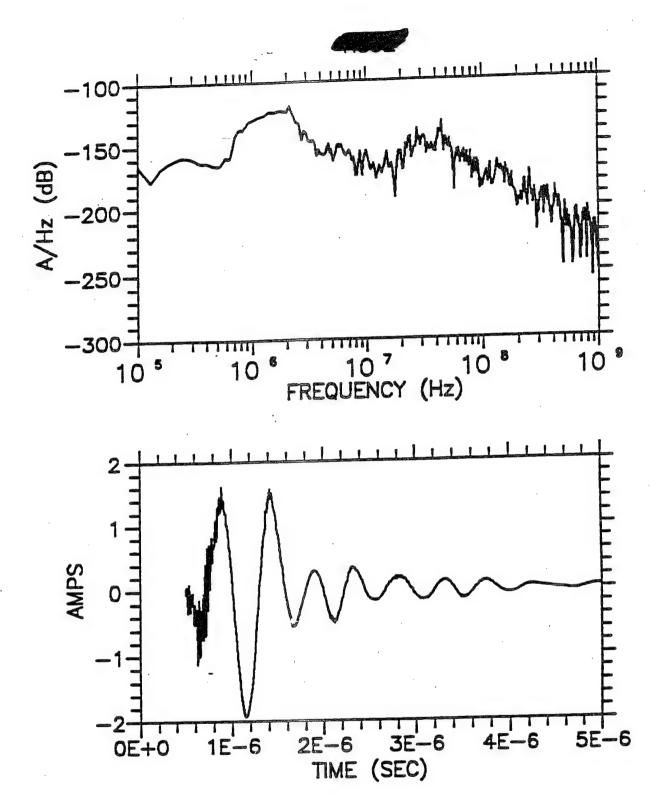


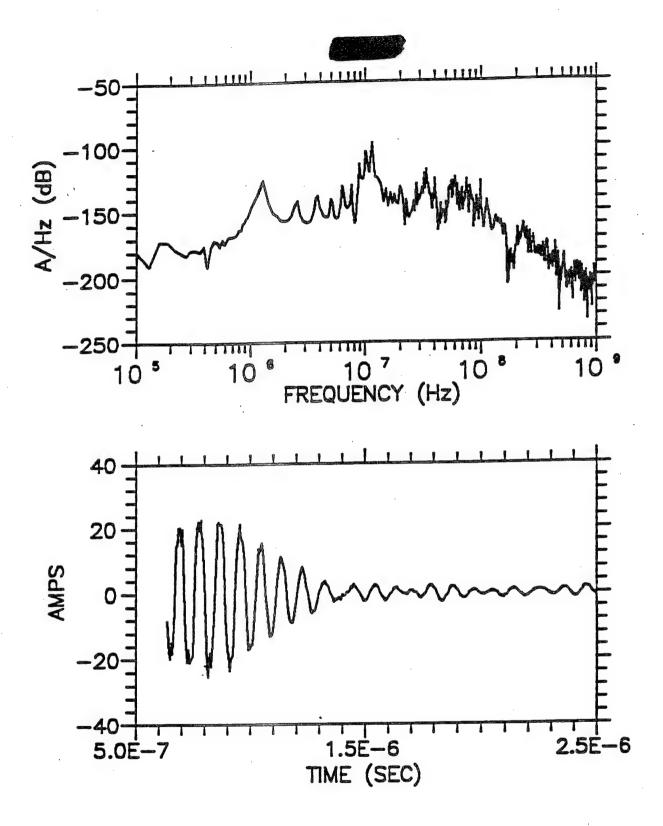


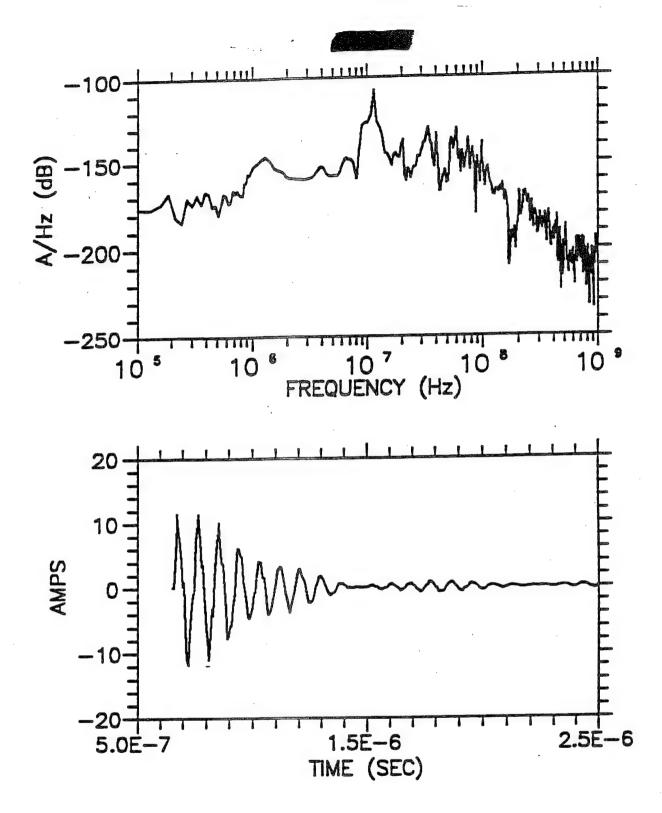


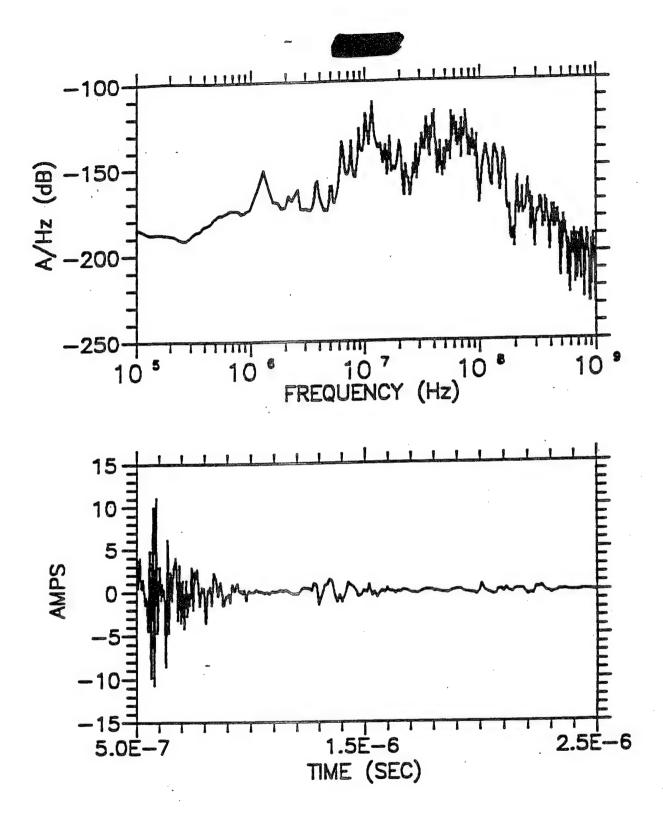


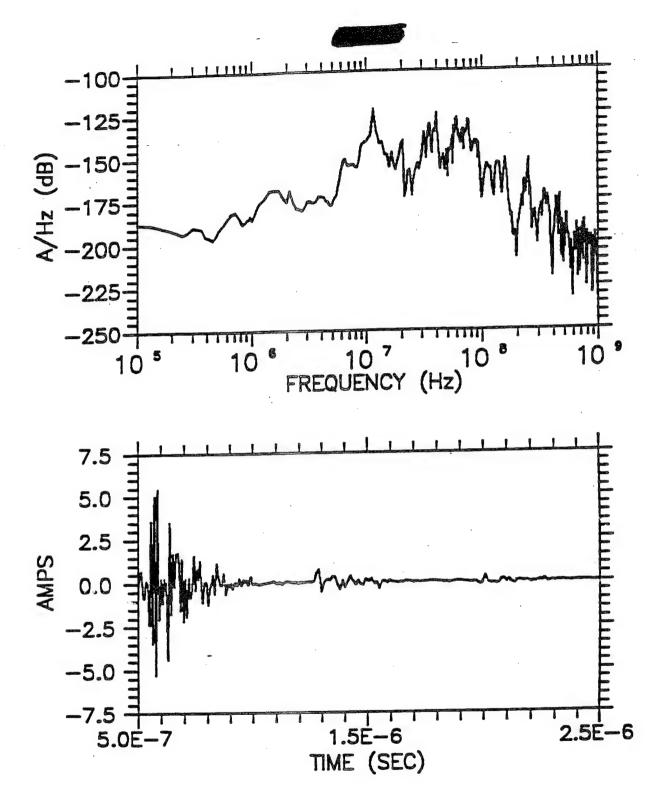


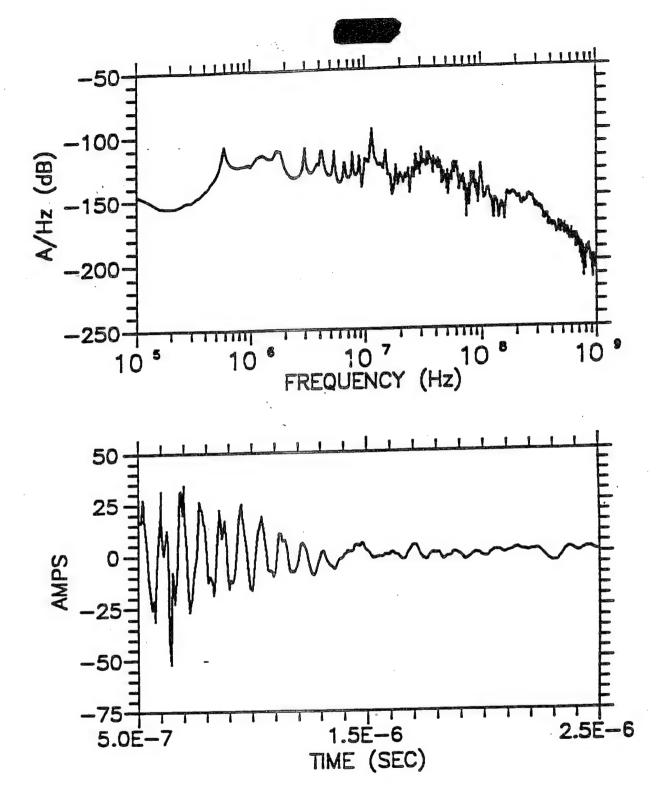


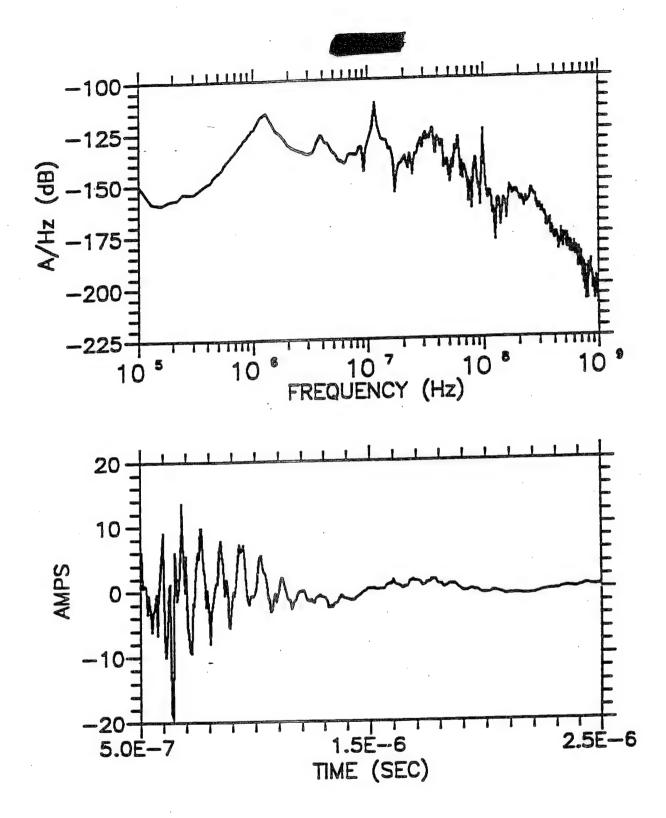


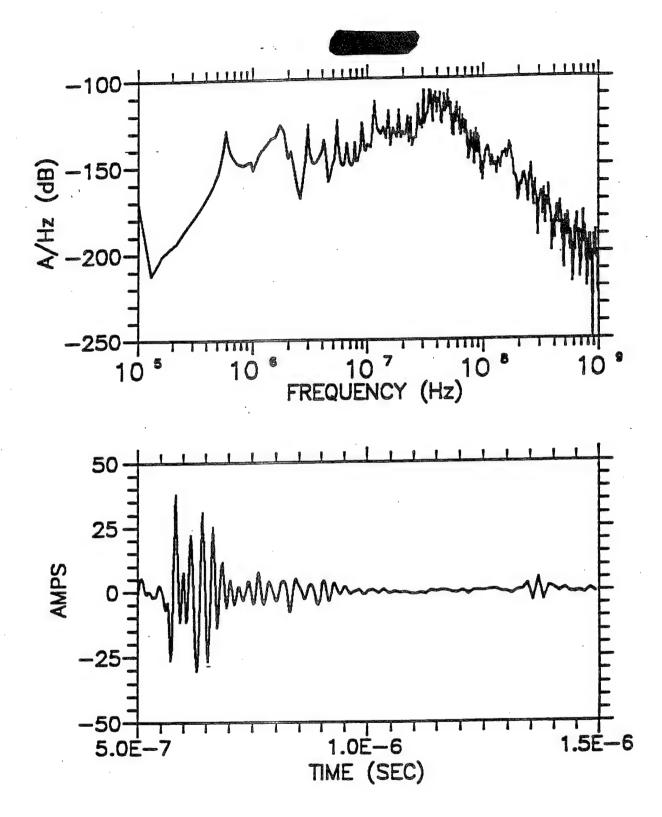


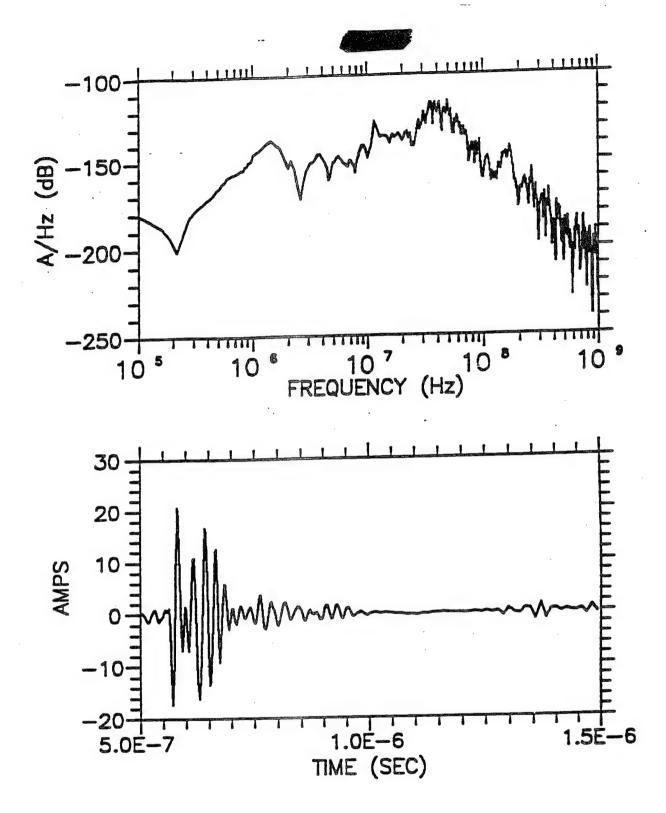


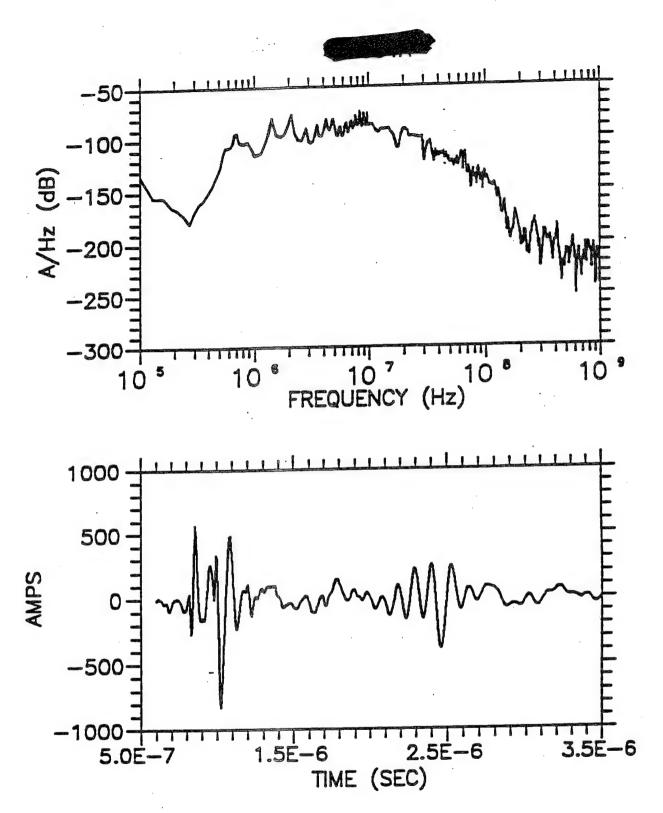


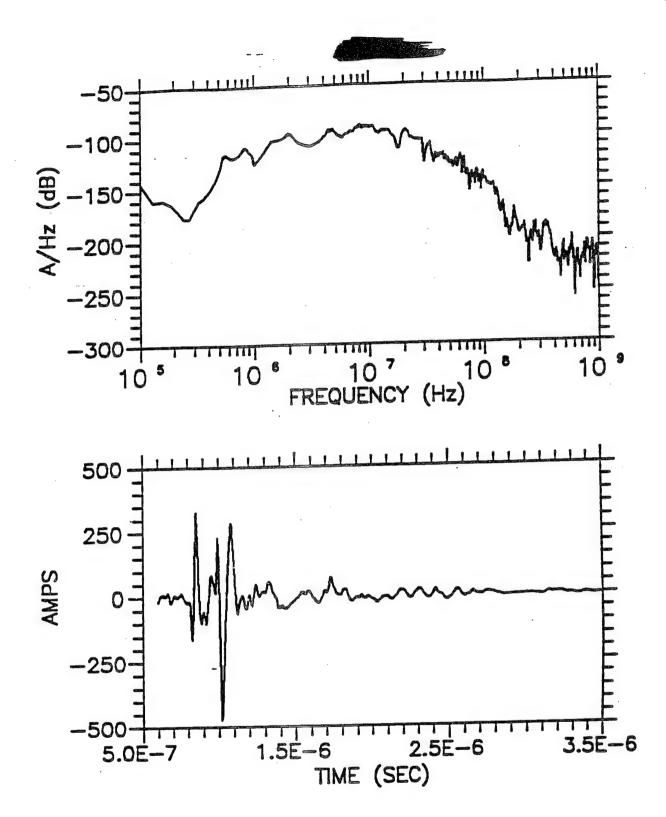


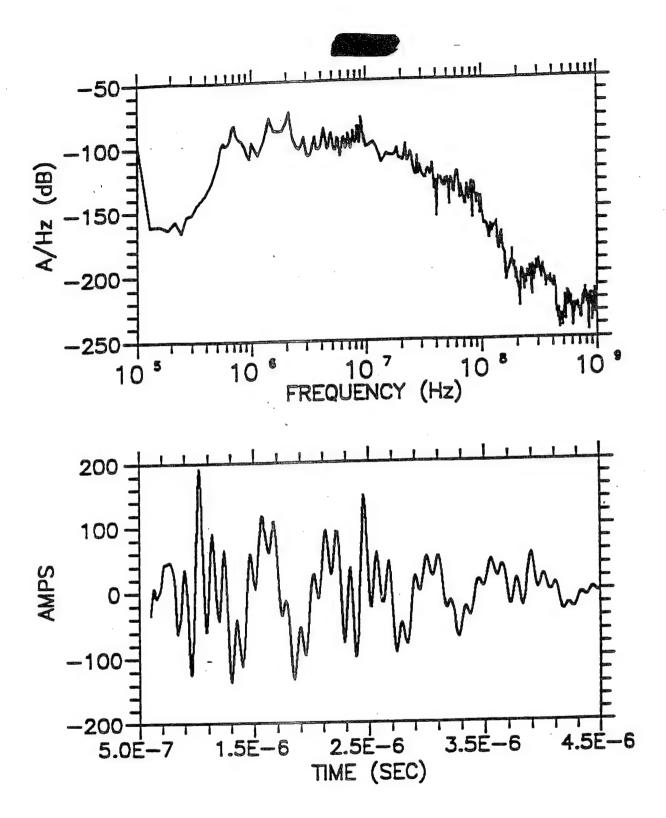


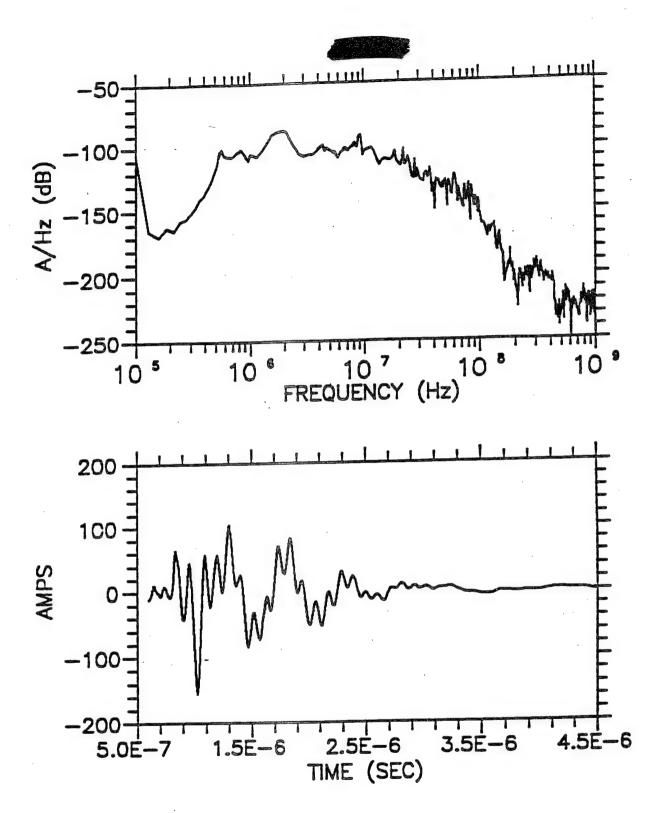


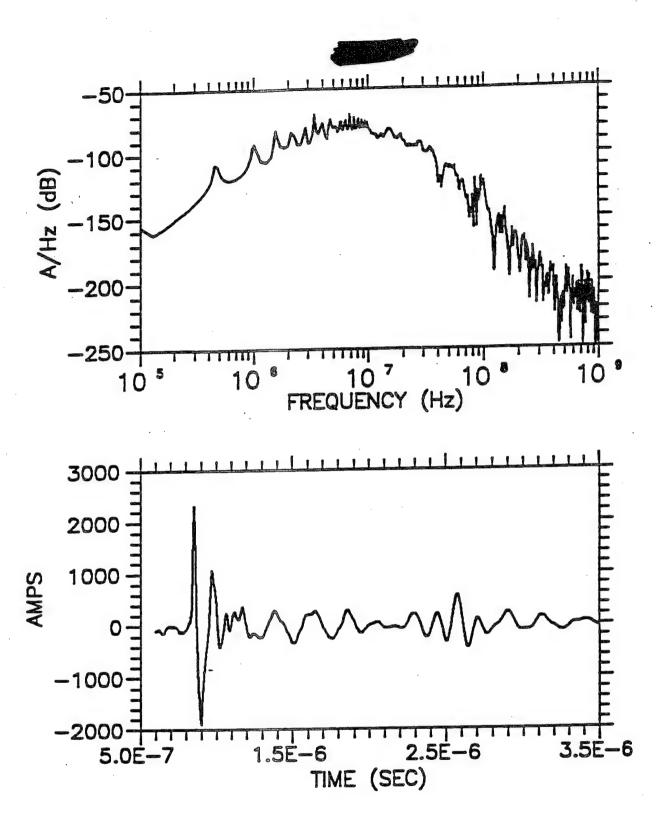


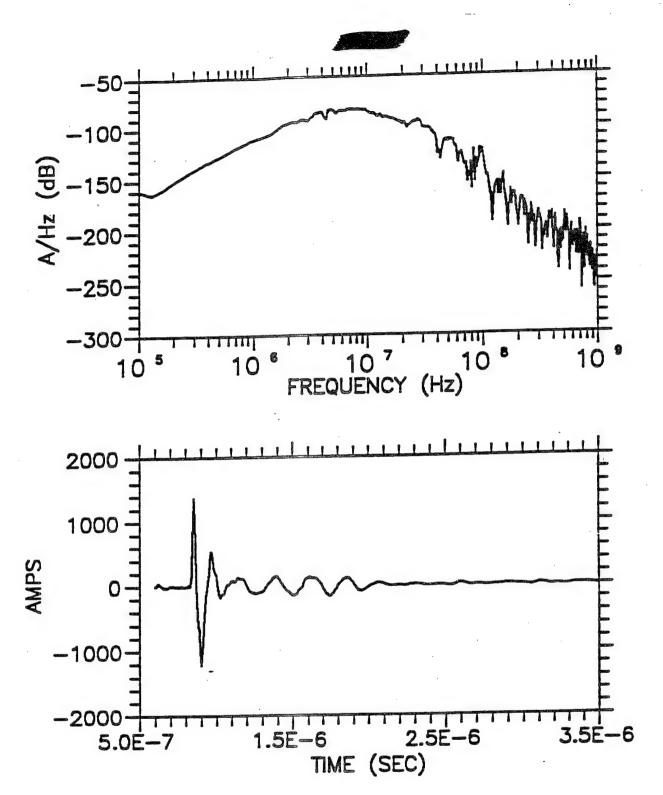


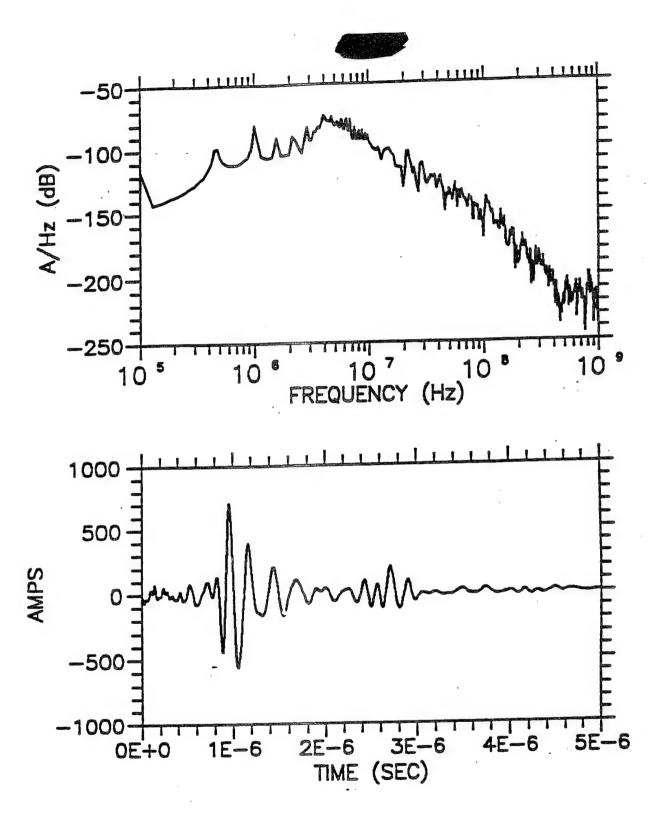


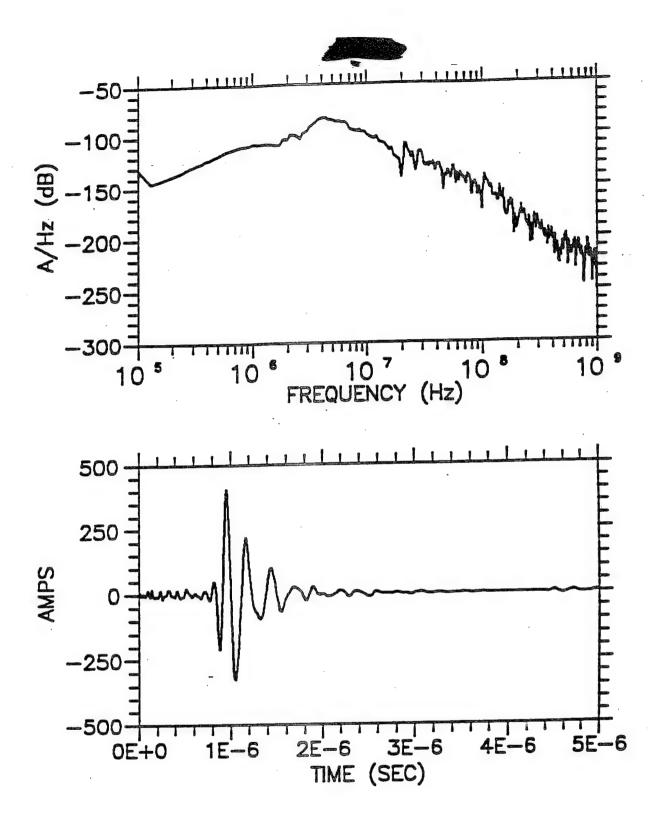


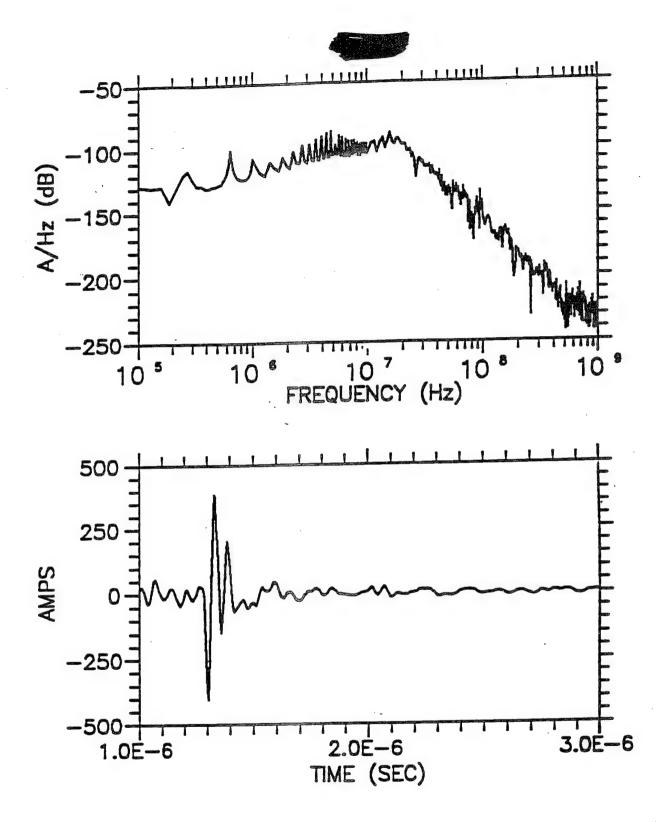


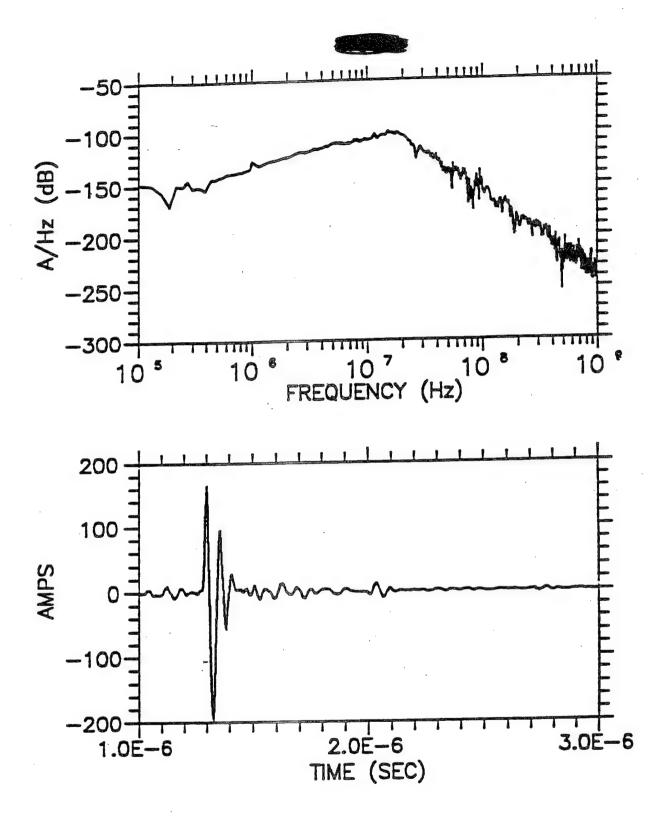












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### APPENDIX D

## SIGNAL TO NOISE PLOTS FOR THE CW ILLUMINATION MEASUREMENTS OF THE ANTENNAS

The upper trace shows the signal; the lower trace shows the corresponding ambient noise. The difference is the signal-to-noise ratio in dB.

dep D 1.0 GHZ -12.0 0.0 10 Hz H011 Source Ampl 256 81g Atten Bandwidth Noise Set Inst Link 100.0 MHz 128 KHZ MHZ 9 9 -40.4B 100.00 1000.0 -182.51 Frequency 10.0 MHz MAP Min MBX Mex 64 Amp 1: Freq: 1.0 MHz **0**0 16: Wide Ares THE HOUSE 08-16-92 35 IC39 100.0 KHZ -190 -430 -180 -170 -460 -110 -120 -100 -140 -150 Description -30 140 -50 000 -70 -80 -90 Point Type Test Time Sig Probe Facility ebust1qmA Test Test D-2

Report

to Noise

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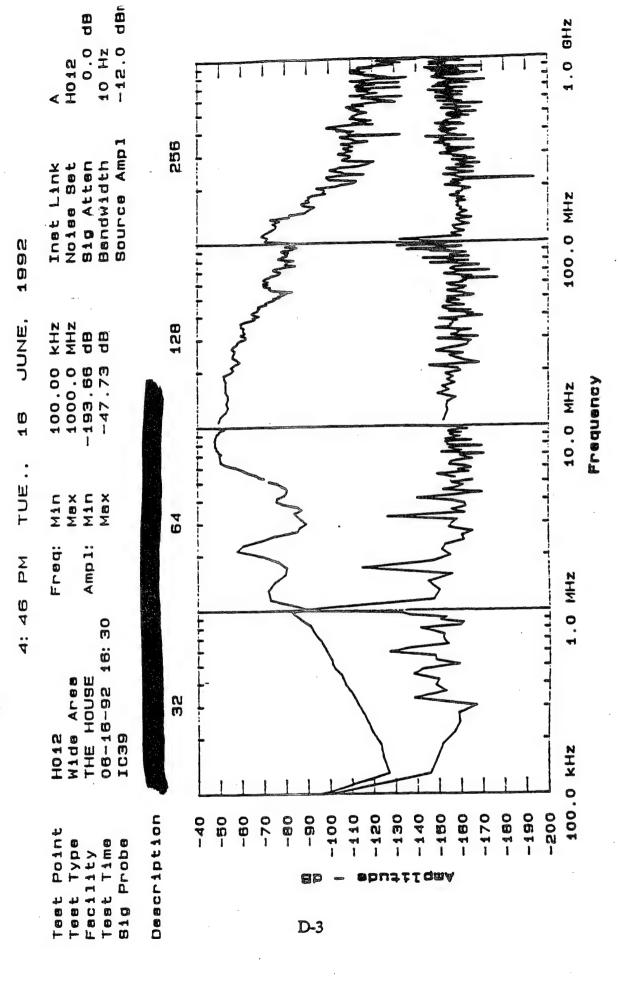
TUE ..

Ω

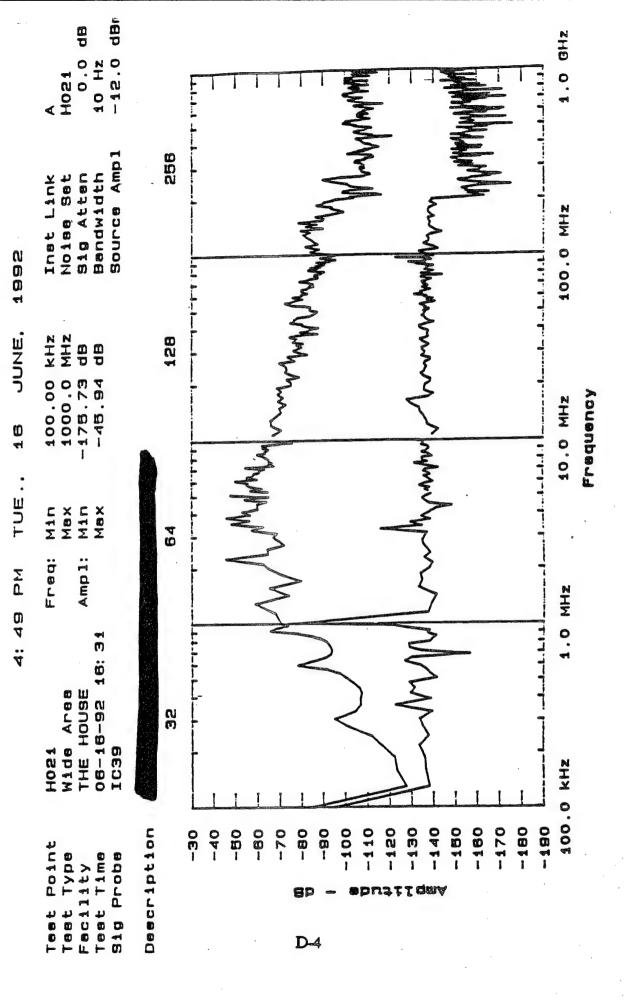
4: 44

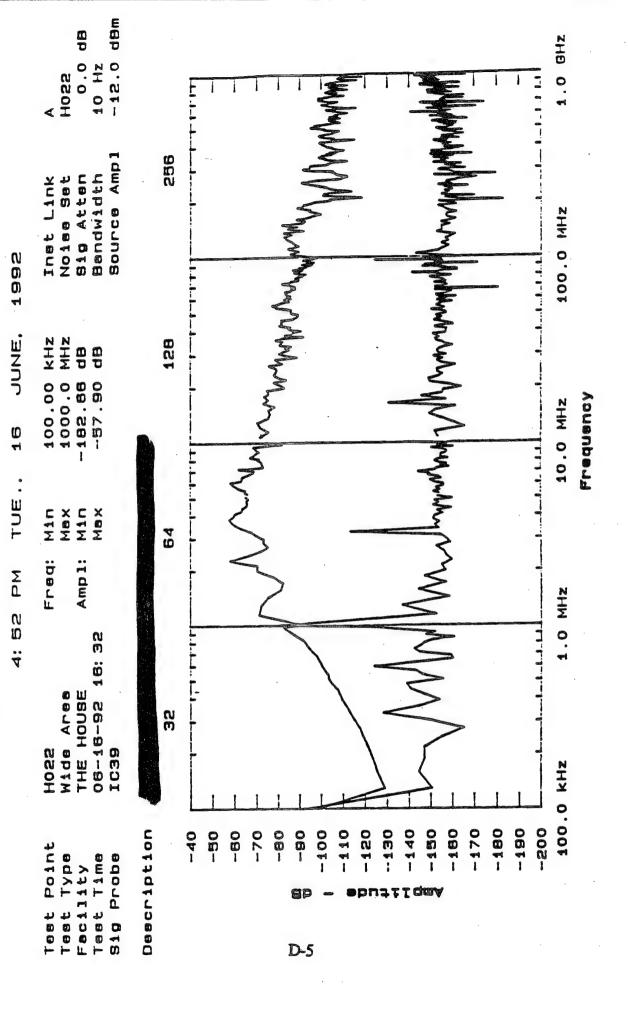
Signal

# Report to Noise Signal

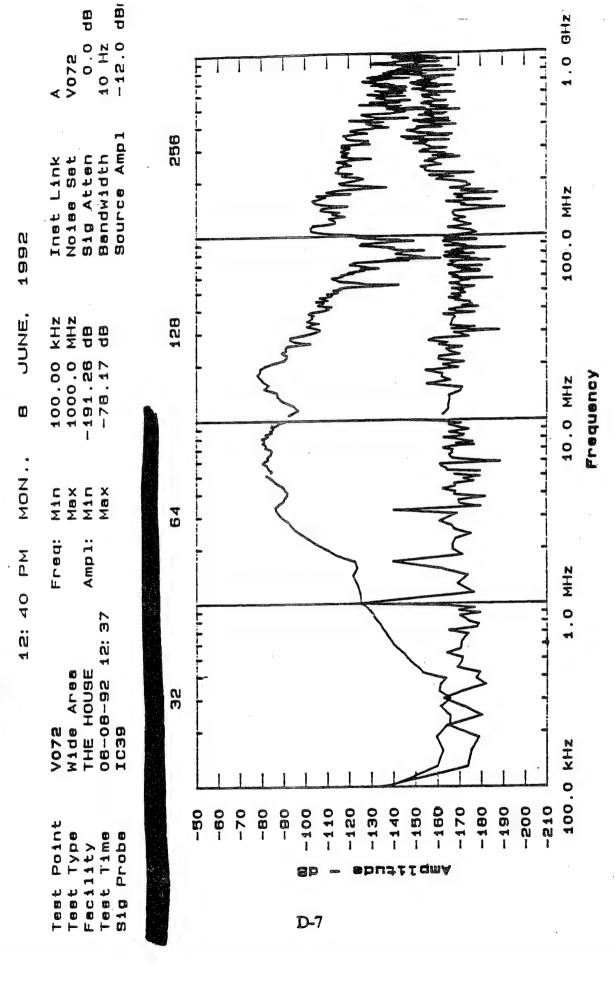


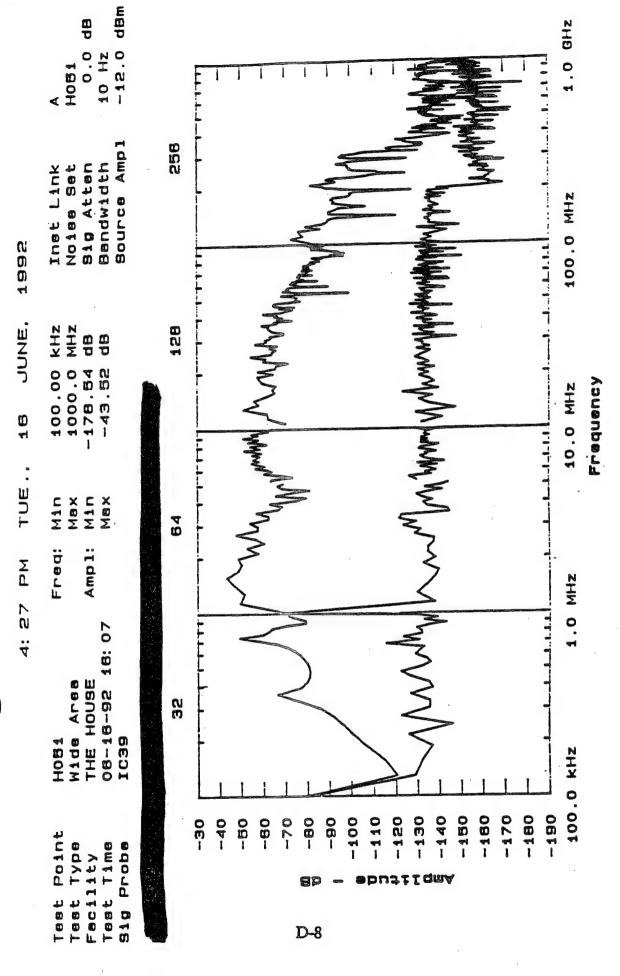
# Report to Noise Signal

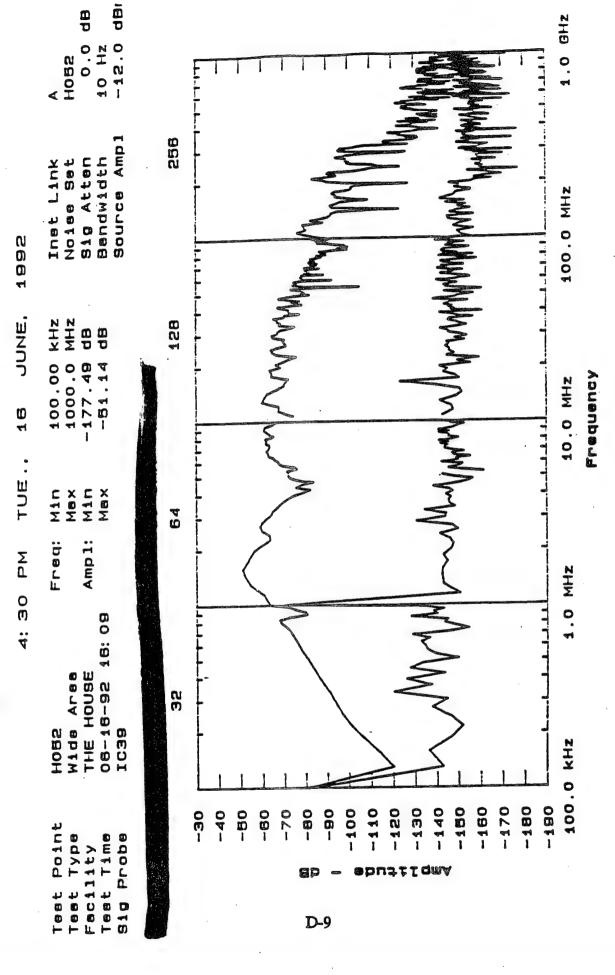




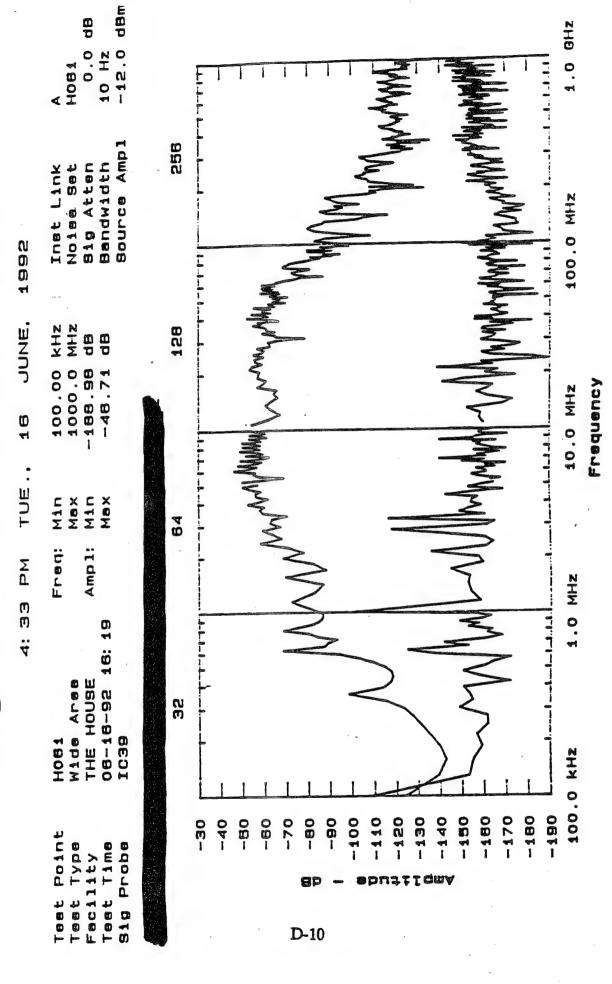
Frequency

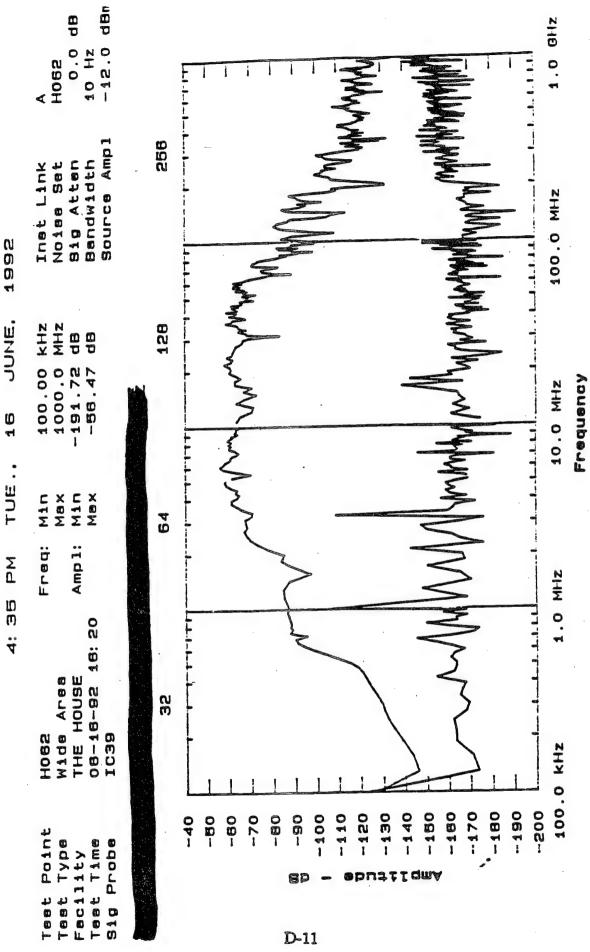


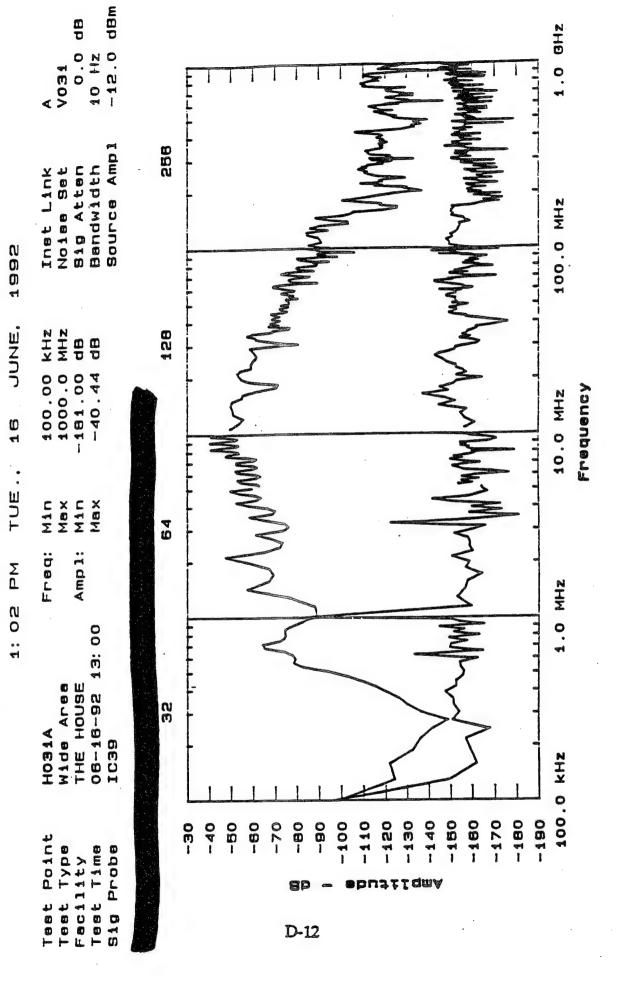




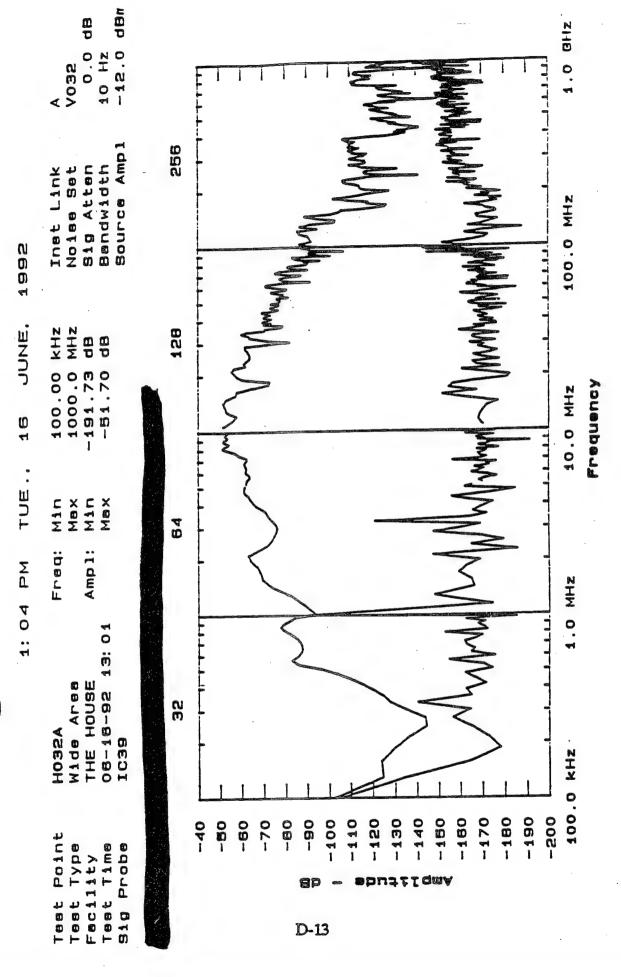
#### Report Noise t 0 Н Signa

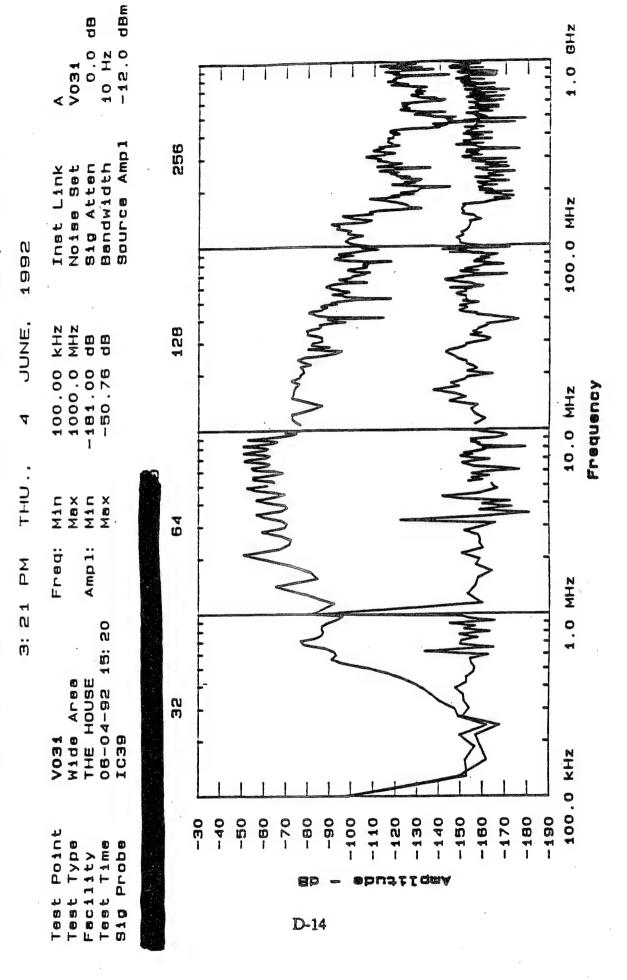






#### Report Noise t O Signal





0.0 -12.0 10 Hz V032 Source Ampl 256 Report Noise Set Sig Atten Bandwidth Inst Link 1992 CUNE. 128 9 q Q to Noise -191.73-62.40 1000,0 100.00 THU: Min Min Max Max 64 Freq: Amp 1: Σ 0 4 Signal 2 (n) 06-04-92 15: THE HOUSE Wide Area 32 **V032** IC39 -160 -180 -140 -150 -170 -110 -130 -100 -120 -60 -70 -80 -90 -50 Point Type T1me Sig Probe Facility abutt I qmA Test Test Test D-15

1.0 GHZ

100.0 MHz

10.0 MHz Frequency

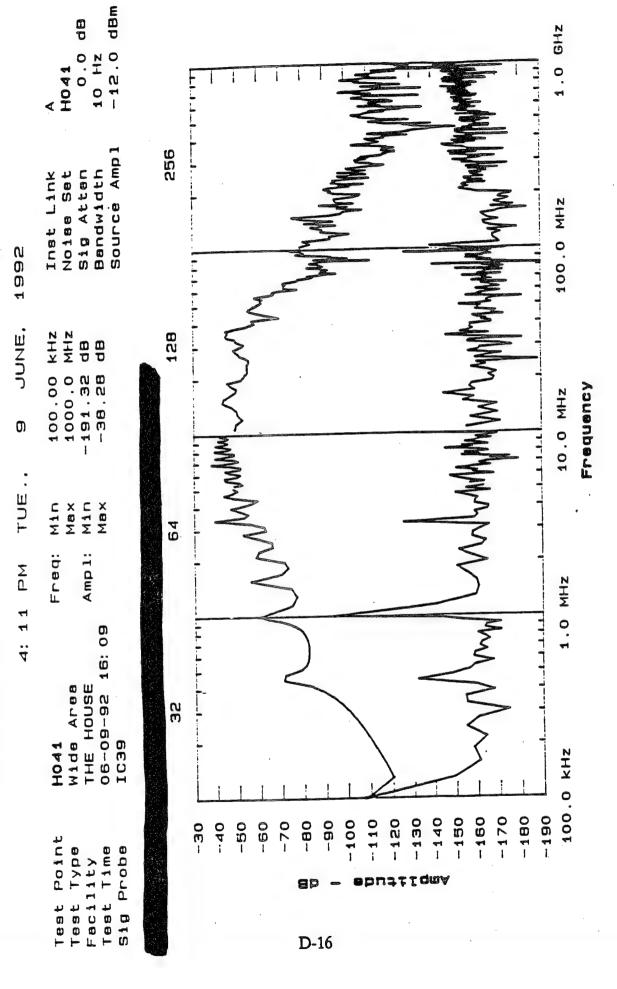
1.0 MHz

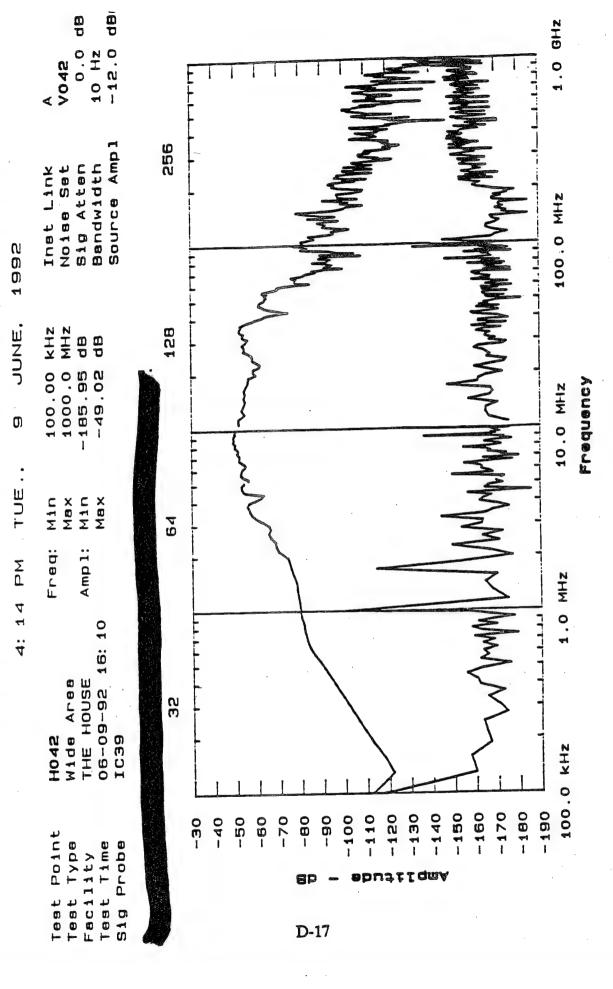
100.0 KHZ

-190

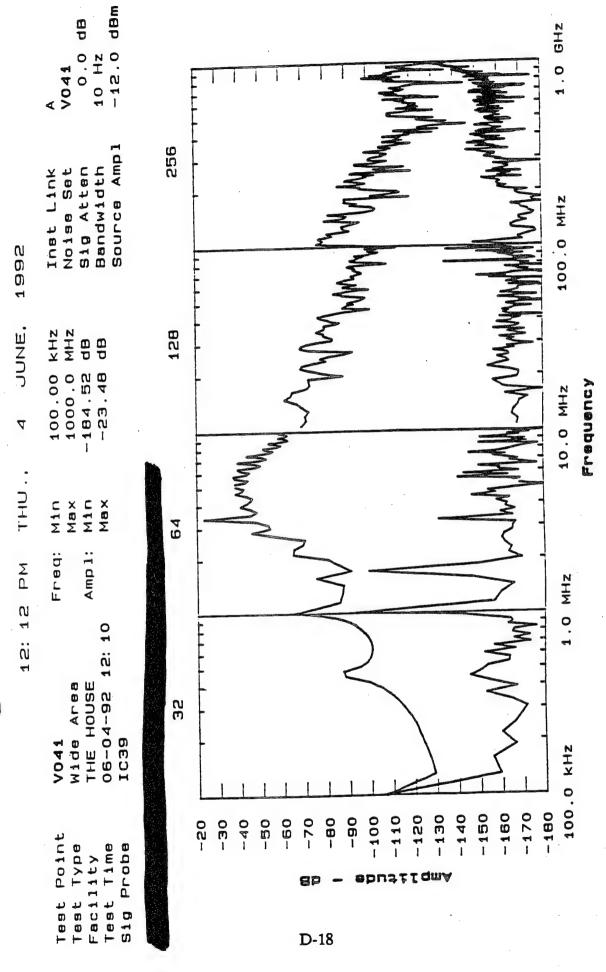
dBr

0

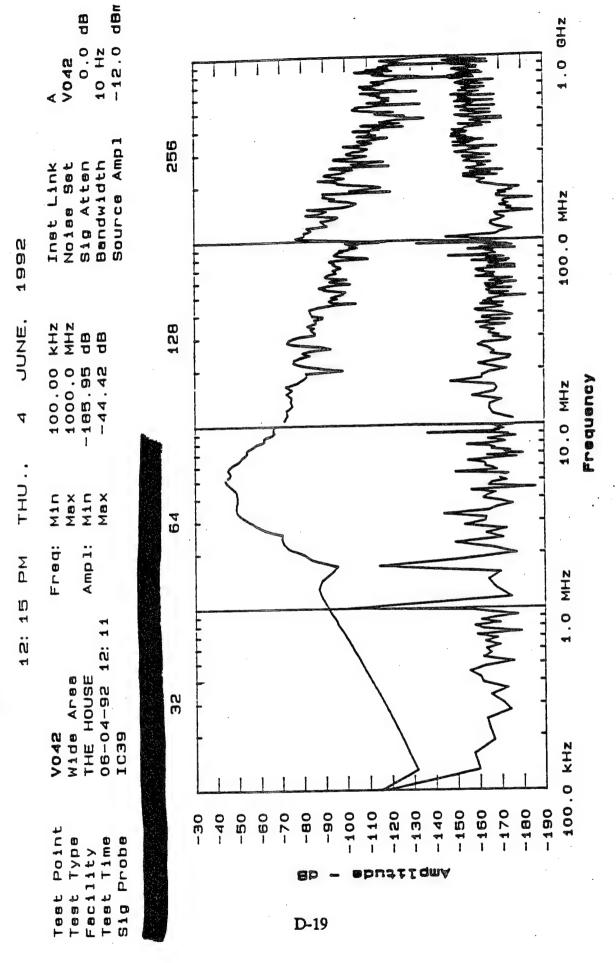


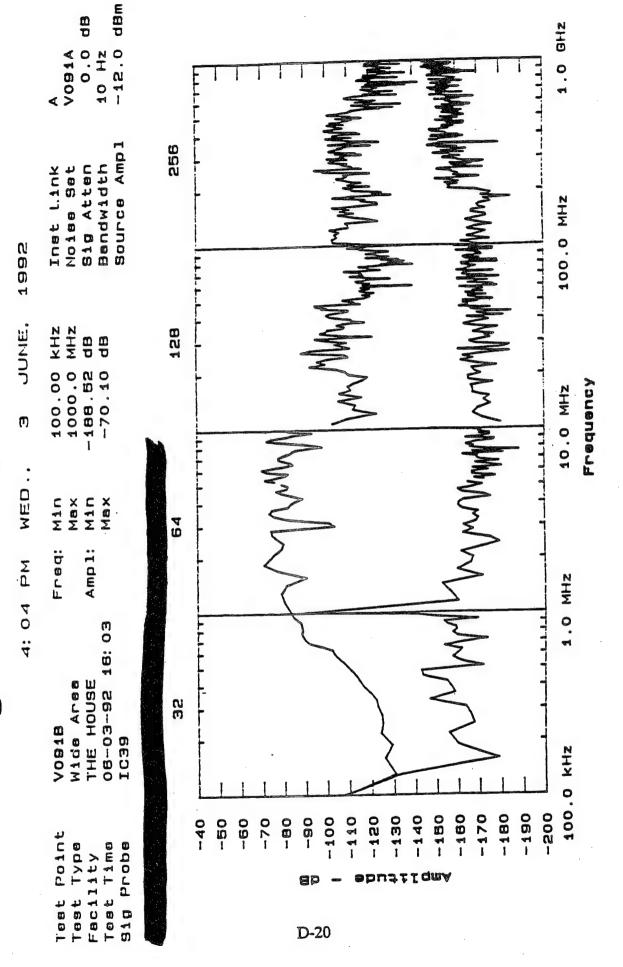


#### Report Noise ر د Signal



#### Report Noise t O Signal





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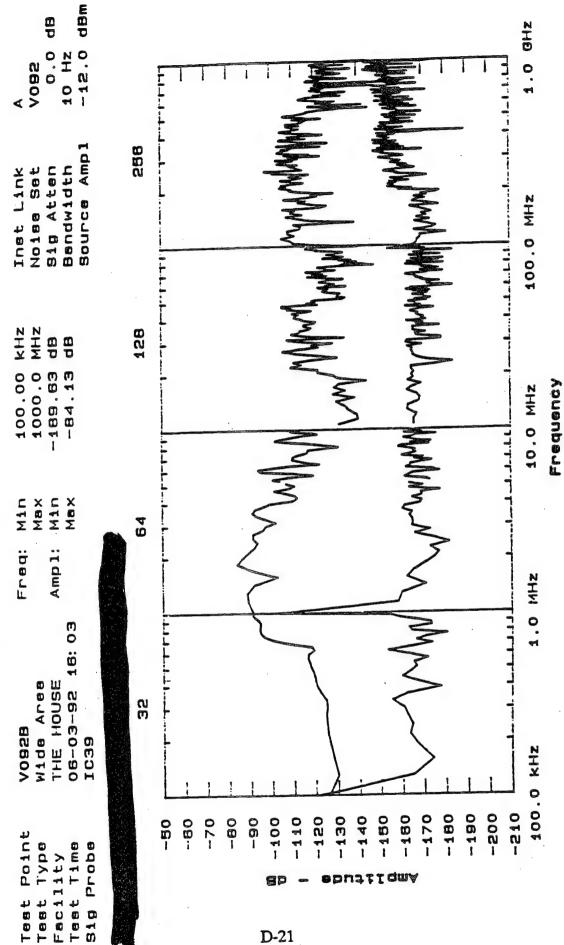
JUNE.

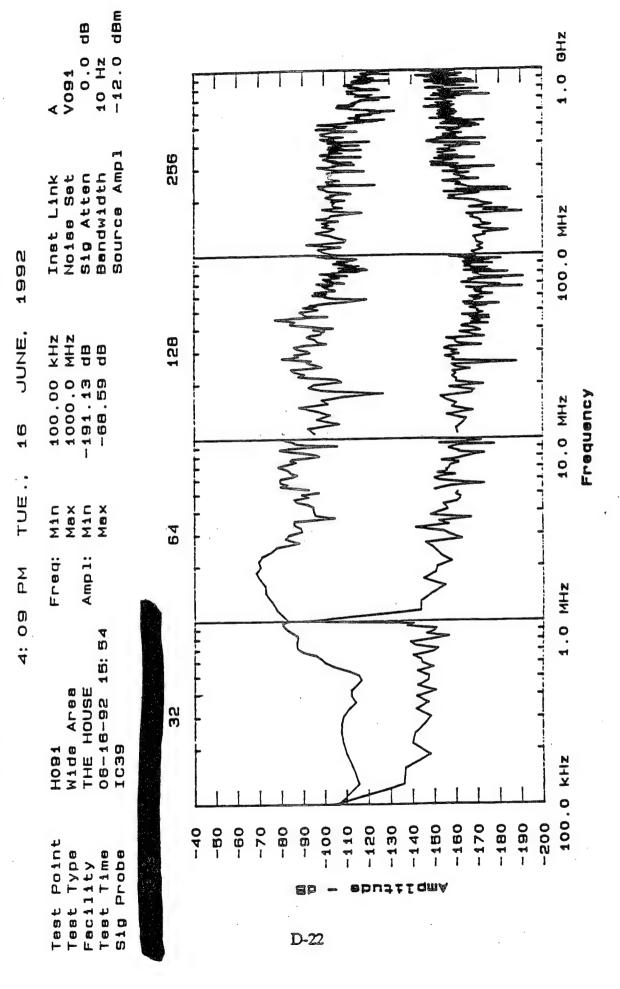
n

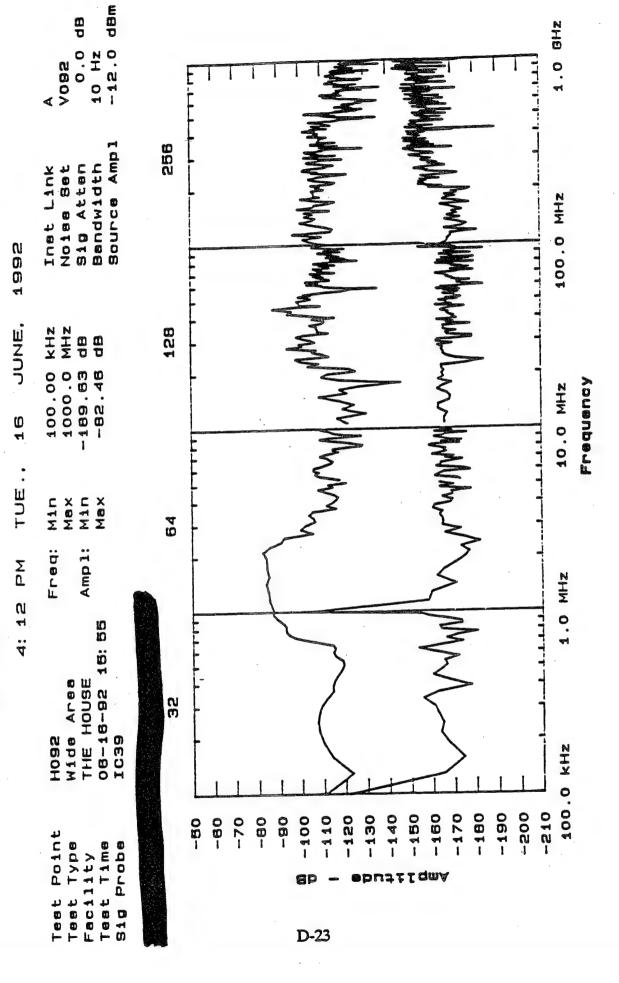
WED:

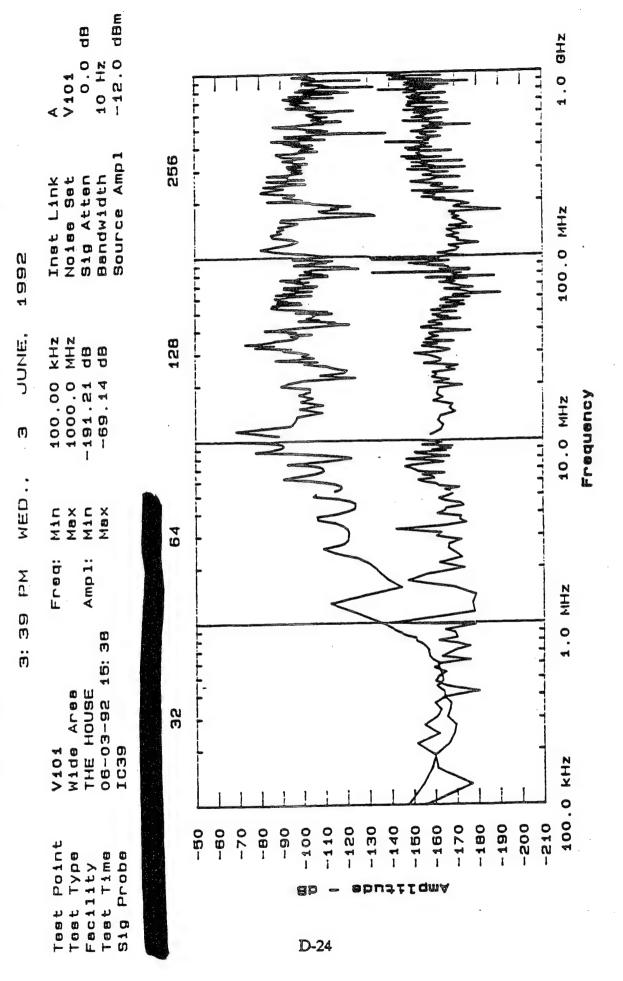
Σ

4:07

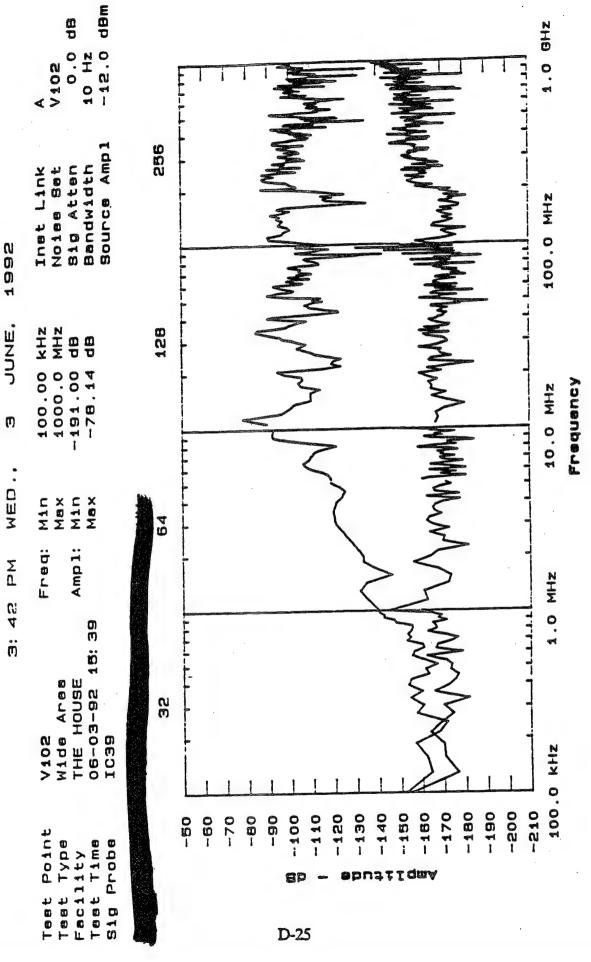




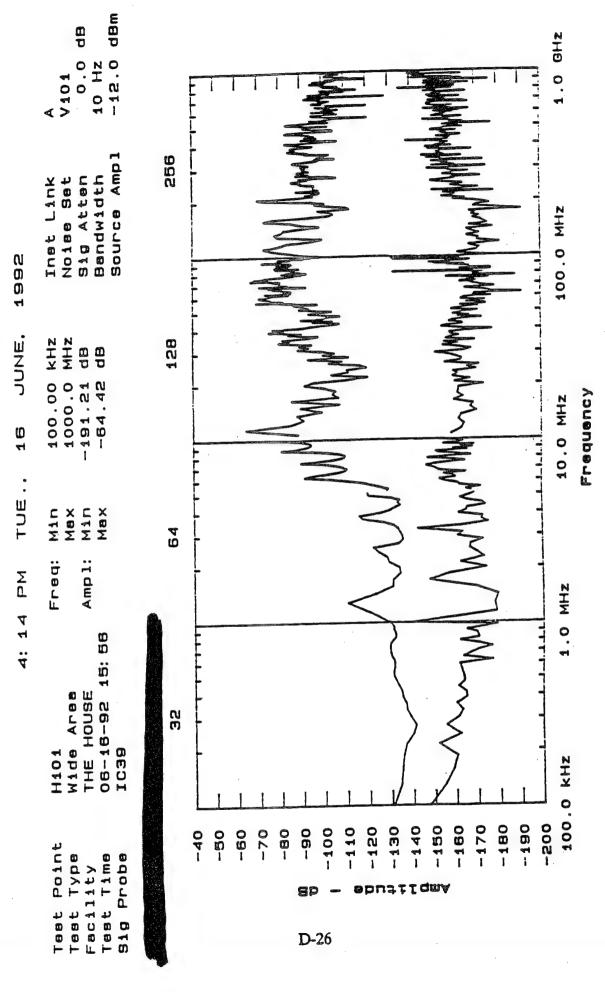


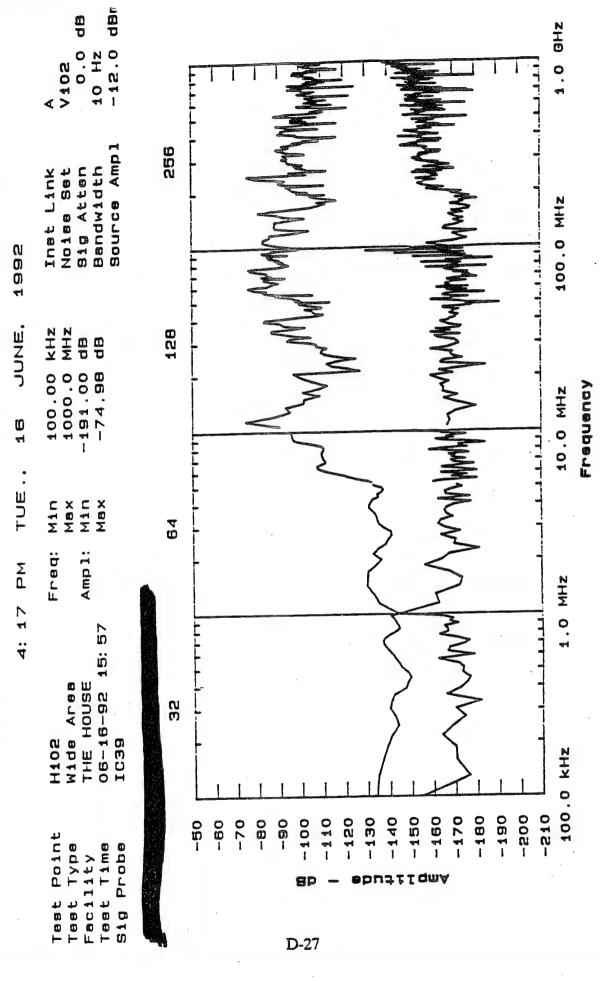


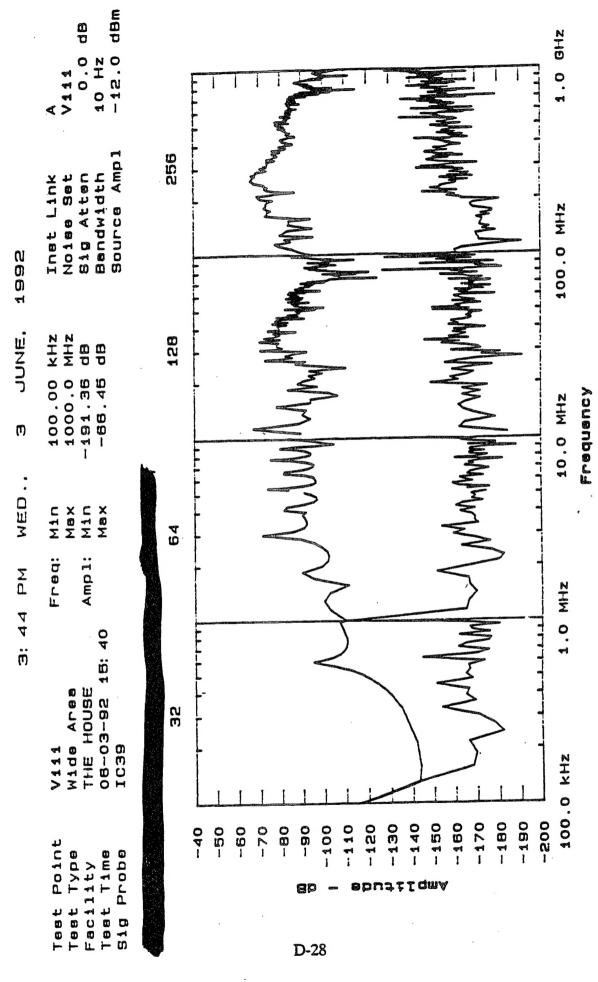
#### Report Noise t O Signal



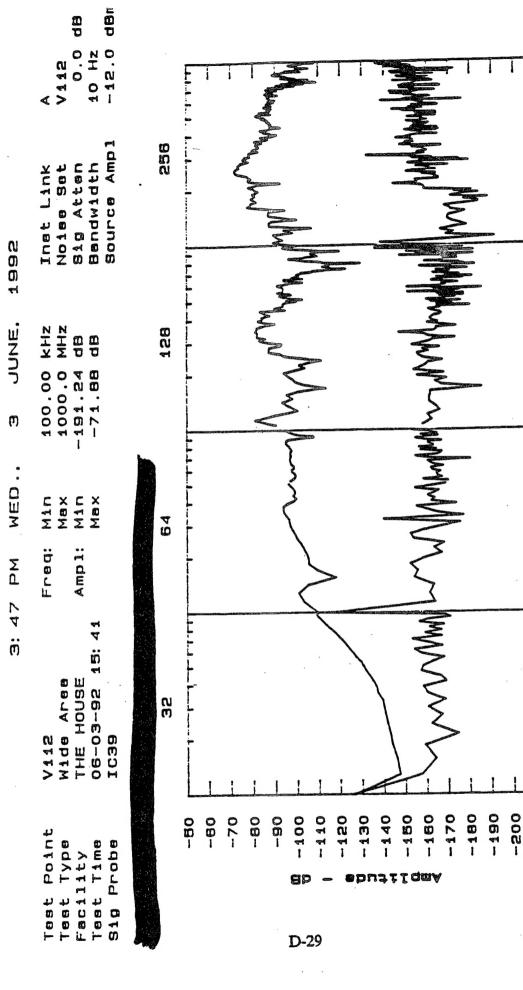
#### Report Noise ر 0 Signal







#### Report Noise t O H Signa



1.0 GHZ

100.0 MHz

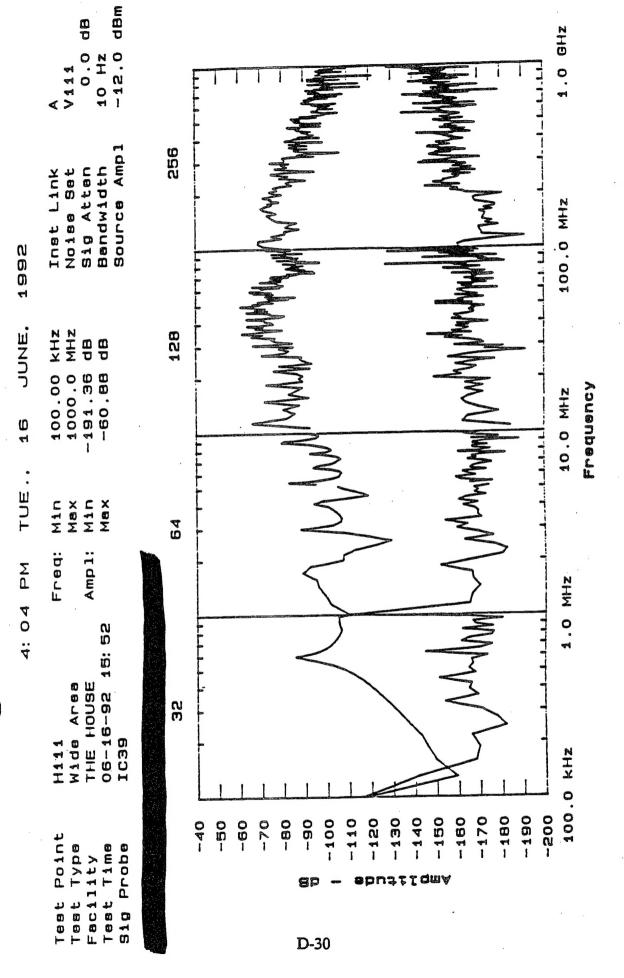
10.0 MHz Frequency

4.0 MHZ

100.0 KHZ

-240

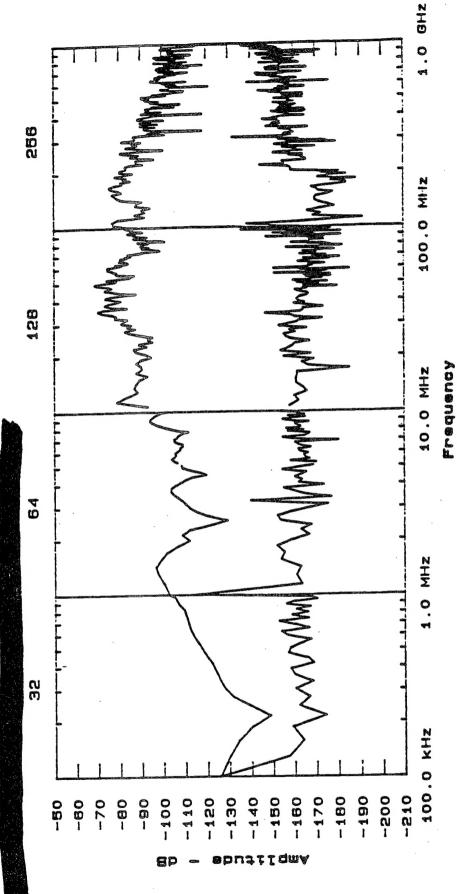
- 4. - L- 1. 1. L. 1.



#### -12.0 0. 10 Hz V112 4 Source Ampl Report Sig Atten Bandwidth Noise Set Inet Link 1992 している。 MHZ 0 Noiso 100.00 -191.24 -69.10 1000.0 10 TUE .. Z L Min χ Θ Σ X ® t O Amp 1: Freq: Σ 4:06 Signal വ 15: THE HOUSE Wide Area 06-16-92 H1120 1C39 Test Point Sig Probe Type Test Time Facility Test

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